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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 5 : G01R 27/02, B65G 1/00

A1

(11) International Publication Number: WO 94/11745

(43) International Publication Date: 26 May 1994 (26.05.94)

(21) International Application Number: PCT/US93/11076

(22) International Filing Date: 10 November 1993 (10.11.93)

(30) Priority data:

07/974,853	10 November 1992 (10.11.92)	US
07/981,801	25 November 1992 (25.11.92)	US

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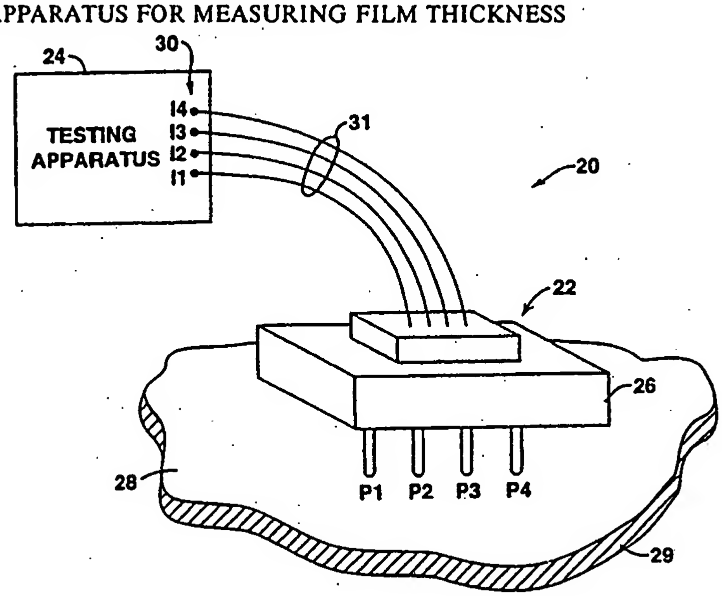
(81) Designated States: JP, KR, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published

With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: METHOD AND APPARATUS FOR MEASURING FILM THICKNESS



(57) Abstract

An apparatus (20) for measuring film thickness and handling wafers is described. A four-point probe (22) engages the surface of a film (28), and a measuring apparatus outputs a voltage waveform which induces a current in the outer probes of the four-point probe and through the surface of the film. The two inner probes measure a voltage in the film created by the current. A sheet resistance of the film is calculated by taking a least square fit of the measured current and voltage and calculating the slope of the least square line fit. The thickness of the film is calculated by dividing the film resistivity by the calculated sheet resistance. An apparatus for handling wafers in which a wafer pick moves along a horizontal x-axis to unload a wafer from a cassette and position the wafer over a chuck (212). The chuck moves upwardly along a z-axis perpendicular to the surface of the wafer and lifts the wafer off the pick. The pick retracts and the four-point assembly moves along the x-axis to position itself over the wafer and chuck with reference to a calculated wafer center. The chuck then moves upwardly to engage the surface of the wafer with the probe. Wafer characteristics, such as film thickness, are tested at several test points on the circle on the surface of the wafer.

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METHOD AND APPARATUS FOR MEASURING FILM THICKNESS

Description

Technical Field

This invention relates to the measurement of film thickness, and more particularly to measuring the sheet resistance of a conductive film on a wafer and handling the wafers in the testing process.

Background Art

Films of various materials are used widely in the manufacture of products. For example, conductive films are often applied to semiconductor wafers as part of a process for manufacturing integrated circuit chips. Many integrated circuits have devices with submicron geometries, requiring very uniform film thicknesses. It is therefore desirable to have a means for measuring film thickness to ensure uniform film deposition.

Testing of film thickness is often done using a test probe assembly that contacts a film 14 formed on a wafer 15, as shown in Figure 1. The probe assembly 10 usually includes four linearly arranged probes 12a-d, where the two outer probes 12a and 12d direct a constant current I through the film 14 and the two inner probes 12b and 12c read the voltage drop created across the film by the current I on a meter 16. Alternatively, probes 12a and 12c can direct the current I and probes 12b and 12d can read the voltage drop. The constant current I is generated by a current source 18. Following the voltage measurement, the sheet resistance can be calculated from the relationship:

$$R = 4.562\frac{V}{I}$$

where V is the voltage measured by the two inner probes and I is the current flowing through the film. This formula assumes that all four probes of the probe assembly 10 are equally spaced apart. The film thickness can be calculated from the relationship:

$$Thickness(cm) = \frac{\rho}{R_{sheet}}$$

where ρ is the resistivity of the film in ohm-cm, and R_{sheet} is the measured sheet resistance.

Four point probe measurement systems have been improved over the basic apparatus described above. In U.S. Patent 3,676,775 by *A. Dupnock*, a method for measuring the resistivity of an epitaxial semiconductor layer is described in which at least two-spaced high conductivity diffused regions are formed in the base wafer prior to deposition of the epitaxial layer, and the four point probe is is located directly over the high conductivity regions. In U.S. Patent 4,989,154 by *Yamashita et al.*, a method and apparatus for measuring resistivity using a four-point probe is described in which a correction coefficient is calculated from shape and position information of the wafer and multiplied by the measured resistance value. The *Yamashita et al.* apparatus includes a computer controller that receives the four point probe measurements through an analog-to-digital (A/D) converter. In U.S. Patent 4,335,350 by *J. Chen*, an apparatus utilizing two probes is described, in which a four point probe is engaged with one surface of a wafer, and another probe is engaged with the other surface in order to measure leakage current from the first probe. Finally, in U.S. Patent 4,703,252 by *Perloff et al.*, an apparatus and method for testing the sheet resistance of a wafer is described in which multiple test readings are taken by a four point probe at predetermined test locations on the wafer.

While the prior art four point probe apparatus have been successful in measuring the sheet resistance and film thickness of wafers, they tend to exhibit some undesirable characteristics. For example, the prior art uses constant current sources to provide the current through the film. Current sources are expensive and slow to stabilize, often requiring five seconds or so to stabilize for each measurement. This stabilization delay is undesirable for production environments, where fast measurements are desired. A further problem with the prior art four-point probe apparatus is the presence of offsets and drifts in the current level of the current source. Inaccurate sheet resistance and film thickness values can result from this problem. A different problem in the prior art is the presence of hysteresis and magnetic effects that occur when different current levels are tested in the wafer. These effects appear when a large jump in current level occurs and can substantially alter a measurement enough so that its accuracy cannot be relied upon.

Thin film testing, as described above, is often accomplished by an automated process, in which robots continuously handle and test, for example, wafers that include the thin films. Robot testing and handling tends to be more efficient than manual testing and handling of wafers, since robots can be much faster and more precise than human operators. Also, robots tend to be less contaminating than humans when handling wafers.

Typical robot wafer handling systems move a wafer into testing position and move a probe assembly to engage the wafer surface and take measurements. Some robot systems also have the ability to remove a wafer from a wafer cassette, set it down on a testing surface, and place the wafer back into the wafer cassette after testing in a process known as cassette-to-cassette handling.

Prior art wafer handling systems vary in structure and method of handling wafers. In U.S. Patent 4,204,155, *M. Terry* describes an automatic four-point probe mechanism that repeatedly lowers a four-point resistivity head onto a semiconductor wafer. In U.S. Patent 4,755,746, *Mallory et al.* describes an automatic system for resistivity testing of semiconductor wafers, and includes a handling system whereby a wafer on a rotatable platform is lowered to a testing area. A probe assembly moves into place over the wafer and lowers so that the probe contacts the wafer to perform tests. In U.S. Patent 4,907,931, *Mallory et al.* describes a semiconductor wafer handling apparatus which automatically moves wafers between wafer cassettes and a wafer test system. A shuttle arm is aligned with a wafer in a cassette and a spatula extends to remove the wafer from the cassette. The shuttle arm then rotates and moves the wafer to a testing area, where the arm lowers and retracts, leaving the wafer to be tested. The wafer is removed and placed into the cassette by the reverse operation.

While the prior art wafer handling and test systems have been successful in handling and testing wafers, they tend to exhibit some undesirable characteristics. For example, the prior art moves both the test probe and the wafer in the direction perpendicular to the wafer surface, where the test probe is moved to engage the probe with the surface of the wafer, and the wafer is moved to facilitate its loading and unloading. This duplication of movement increases costs of the wafer handling equipment due to the extra motors and controls that are required. A further problem with the prior art wafer handling system is the complexity of the handling apparatus. The wafer-handling shuttle arm in the prior art requires several motors and must move along several axes to position a wafer correctly on a test area. Complex robots

are expensive and require a great deal of maintenance to keep them operating correctly. Such costs and maintenance are undesirable in production environments.

What is needed is an apparatus and method that will handle and test a wafer efficiently and economically. Wafers would therefore be tested faster and with less production and maintenance costs, thereby increasing the amount of manufactured products and revenue. What is further needed is an apparatus and method that will quickly test a wafer for resistivity and thickness so that many measurements of a wafer's surface can be taken and more wafers can be tested in a given amount of time. In addition, an apparatus and method are needed that will eliminate the hysteresis and magnetic effects of taking a measurment with a probe so as to increase the accuracy of the measurements.

Disclosure of the Invention

The present invention addresses the problems in the prior art by providing a method and apparatus to measure film thickness by coupling a variable voltage source to the outer probes of a probe assembly to provide a variable current through the film. The variable current does not need to stabilize before measurement of film thickness. Probe measurements are taken at many different voltage levels to provide a more accurate overall sheet resistance measurement. These improvements allow measurements to be taken in a shorter amount of time with more accuracy.

The present invention also addresses the problems in the prior art by providing a method and apparatus for handling wafers by moving the wafers and probe assembly along a horizontal axis and moving a chuck in the direction perpendicular to the surface of the wafer to engage the probe assembly. Only five axes of movement are required for complete cassette-to-cassette testing in the present invention, as opposed to six or more axes of movement required in the prior art.

In one aspect of the invention, an apparatus for measuring film thickness comprises a variable voltage source coupled to the outer probes of a four point probe assembly by a sense resistor. The four point probe assembly engages the surface of a conductive film on a substrate so that a current flows through the surface of the film between the two outer probes. The voltage source preferably includes a digital computer connected to a digital-to-analog converter (DAC) which produces a

sawtooth voltage waveform. This sawtooth waveform is then amplified prior to being applied to the four point probe.

The current flowing through the film is measured by measuring the voltage across the sense resistor and applying Ohm's law ($I = V/R$). Both the voltage across the sense resistor and the voltage between the inner probes of the four point probe are measured using variable gain differential amplifiers. The differential amplifiers send their respective outputs to analog-to-digital converters (ADCs), which provide digital signals to the digital computer. The computer can then calculate the sheet resistance in the surface of the film from the ratio of the current to the voltage across the inner probes. A sheet resistance is preferably measured for a number of input voltage levels in the sawtooth-shaped waveform. For each sheet resistance measurement taken, a film thickness is calculated using the known resistivity of the film material.

The present invention has the advantage of measuring I and V rather than assuming I for the sheet resistance measurements. The present invention also has the advantage of measuring the sheet resistance of the film using a least square fit of the voltage measurements and calculating the slope of the least square line. The sheet resistance is proportional to the slope of this line. Since a slope is measured, the resistance measurement is not sensitive to drifts and offsets in the voltage source or in the entire electronic system.

The present invention also has the advantage of taking many measurements at different current levels in a small amount of time. With many more measurements, the accuracy of the resistance measurement is greatly increased. Also, since the voltage source generates a voltage waveform instead of a constant current, the invention does not have a delay time that is required for a current source to stabilize. As a result, many more measurements can be taken in a given amount of time, which speeds up the entire process and allows more substrates to be tested. Finally, the measurements are taken with a sawtooth-shaped input voltage waveform, which is continuous and has no large current jumps; this waveform shape tends to eliminate magnetic effects of the film and thus degausses the measurement.

In a further aspect of the present invention, an apparatus for handling wafers comprises a wafer pick operative to pick up a wafer and transport the wafer to a test area. The pick moves in a horizontal plane and stops when the wafer is positioned over a rotatable chuck. The chuck moves upward to engage the wafer and the pick retracts from the chuck, leaving the wafer behind. A test probe assembly then moves in the same plane as the pick to position itself over the wafer. The chuck then moves

upwardly so that the surface of the wafer engages the probe assembly for testing purposes.

The probe assembly preferably tests the wafer at several locations on the surface of the wafer. Preferably, the center of the wafer and the wafer flat are found to provide a reference for the test point locations. Once the measurements on one location on the wafer surface are completed, the chuck preferably moves downward and rotates. The chuck then moves upwardly to engage the probe with the wafer surface at a new location and measurements are made. Once all the points in a circular path on the wafer surface are tested, the probe assembly indexes horizontally and another circular path on the wafer surface is tested. Substantially all of the wafer surface can be tested in this manner.

The apparatus includes a wafer cassette assembly that moves the cassette upwardly and downwardly so that the pick has access to all the wafers in the cassette. The pick can remove each wafer held in the cassette, carry each wafer to the chuck to be tested, and load each wafer back into the cassette.

The present invention has the advantage of moving only the chuck upwardly and downwardly, thereby reducing the number of motions required for the testing apparatus and saving cost and maintenance. The present invention also has the advantage of moving the pick and the probe in the same horizontal plane along the same axis, thereby reducing the complexity of the apparatus and saving production and maintenance costs.

These and other advantages of the present invention will become apparent to those skilled in the art after reading the following descriptions and studying the various figures of the drawings.

Brief Description of the Drawings

Figure 1 is a schematic view of a prior art four point probe;

Figure 2 is a perspective view of a four point probe connected to a measurement apparatus;

Figure 3 is schematic diagram of a measurement apparatus;

Figure 4 is graph of the output sawtooth waveform and the corresponding sense voltage and probe voltage waveforms;

Figure 5 is a flow diagram of a method to calculate film thickness;

Figure 6 is a flow diagram of a method to measure sheet resistance using a time variant waveform; and

Figure 7 is a graph of measurements of the sense voltage vs. the voltage across the inner probes of the four-point probe.

Figure 8 is a perspective view of a wafer handling apparatus of the present invention;

Figures 9a-9d are four sequential top plan views of the wafer handling apparatus;

Figure 10 is a side elevational view of the wafer handling apparatus;

Figure 11 is a flow diagram of the wafer handling process;

Figure 12 is a flow diagram of a method to run the testing of a wafer with a probe assembly of the present invention; and

Figures 13a-13c are top plan views of different testing patterns on a wafer surface.

Best Modes for Carrying out the Invention

A prior art four point probe measurement system was shown in Figure 1. In Figure 2, an apparatus for measuring film thickness 20 is shown for the present invention. Apparatus 20 comprises a test probe assembly 22 and a testing apparatus 24. The assembly 22 comprises test probes P1, P2, P3 and P4 that extend from a housing 26, i.e., there are four test probes in the preferred embodiment, aligned in the

standard four-point probe configuration. The test probes P1-4 are preferably spring biased to prevent damage to the film and substrate. The test probes P1-4 engage a film surface 28 on a substrate 29. The film is most typically a metal film such as aluminum (Al), tungsten (W), or a metal alloy such as titanium nitride (TiN), titanium tungsten (TiW), tungsten silicide (WSi), or doped silicon. The springs connecting the probes to the housing allow the probes to shift vertically and thus prevent the probes from marking or damaging the film surface 28 when they contact the film and provide a good contact between each of the probes and the film surface. Each probe P1-4 is connected to a terminal I1, I2, I3, or I4 (I1-4) of the probe assembly connections 30, located on the testing apparatus 24 (described below); where probe P1 is connected to terminal I1, probe P2 is connected to terminal I2, probe P3 is connected to terminal I3, and probe P4 is connected to terminal I4. The connection is made through insulated wires 31. Test probe assembly 22 engages a thin film surface preferably using the handling apparatus described with reference to Figures 8-13.

Figure 3 shows a testing apparatus 24 to measure the sheet resistance and thickness of a film. The preferred embodiment of the testing apparatus 24 comprises a voltage source 34, probe assembly connections 30, a current sensing means 36, and a voltage sensing means 40.

The voltage source 24 includes a digital computer 44, a digital to analog converter (DAC) 46, and an amplifier 48. The digital computer 44 is a programmable device including a microprocessor and an output interface. A suitable digital computer is an AT class IBM compatible personal computer. The computer is coupled to a DAC 46 by a parallel bus 47. In the preferred embodiment, the bus comprises twelve parallel lines, so that the range of binary numbers received by the DAC is 0 to $2^{12} - 1 = 4095$; a 16-bit or higher resolution DAC can also be used. The computer is programmed to send signals to the DAC that are within the range of -5 to +5 volts. The DAC 46 is thus able to output 4096 different voltage levels ranging from -5 volts to +5 volts. A suitable DAC 46 is made by Analog Devices and has a part number AD7237.

The input of amplifier 48 is coupled to the output of DAC 46. Amplifier 48 preferably has a high gain and thus a high output current. A high current is needed to flow through the film 28 so that the voltage across the inner probes P2 and P3 is large enough to be measured accurately. The amplifier 48 in the preferred embodiment outputs a voltage that ranges from -35 to +35 volts. This voltage is the output voltage of the voltage source 34. A suitable amplifier 48 is made by Burr Brown and has a part number OPA541.

The probe assembly connections 30 comprise terminals I1-I4. The terminals are connected to the probes P1-P4, respectively, of the probe assembly 22, as described above, and terminal I1 is also coupled to the output of the voltage source 34 by a sense resistor as explained below. The voltage produced by source 34 flows through the sense resistor, through probe P1, through the film 28, through probe P4, and to ground at terminal I4. Terminals I2 and I3 are connected to probes P2 and P3, respectively, to measure a voltage across the film. In an alternative arrangement, the voltage flows through the sense resistor, through probe P1, through the film 28, through probe P3, and to a ground connection at terminal I3. In this alternative arrangement, the voltage is sensed by probes P2 and P4, connected to terminals I2 and I4, respectively, and the voltage sensing means 40 (described below) is connected to terminals I2 and I4 instead of terminals I2 and I3.

Voltage source 34 is coupled to terminal I1 by a current sensing means 36, which includes a sense resistor 50, a differential amplifier 52, and an analog-to-digital converter (ADC) 54. Sense resistor 50 is coupled between the output of the voltage source 34 and the terminal I1, as explained above. The value for the sense resistor 50 can vary between 10 to 10,000 ohms; the value is adjusted to optimize the sensitivity of the measurements and varies for different films with different resistivities. The sense resistance and gain of the differential amplifier 52 (see below) allow measurements to have a dynamic range of 10^{12} to 1.

Differential amplifier 52 measures the voltage V_{sense} across the sense resistor 50. The differential amplifier in the preferred embodiment is an Analog Devices AD524 or equivalent amplifier. The two input terminals of the differential amplifier are each coupled to one terminal of the sense resistor. Differential amplifier 52 measures V_{sense} across the sense resistor 50 and outputs a voltage adjusted according to the variable gain G_{14} of the differential amplifier 52. The gain G_{14} can be set to different levels by the computer 44 by sending a control signal on control line 53 to set gain tabs on the differential amplifier 52. In the preferred embodiment, gain G_{14} can be set at 1, 10, 100 or 1000. The gain is set to maximize the range of the ADC 54.

The output of the differential amplifier 52 is coupled to an analog-to-digital converter (ADC) 54. The ADC in the preferred embodiment is an Analog Devices AD574. The ADC 54 inputs a range of voltages and has a resolution of twelve bits; a higher resolution ADC can also be used. A range of binary signals from 0 to 4096 can be sent on the twelve bit bus 55 coupled to the output of the ADC. The bus 55 is

coupled to an input port of a digital computer; the digital computer 44 of the voltage source 34 is preferably used. The computer receives data over the bus 55, which is the signal A representing the sense voltage V_{sense} across the sense resistor 50. The computer calculates the current I_{sense} through the sense resistor by dividing the sense voltage V_{sense} by the known sense resistance value R_{sense}. I_{sense} is equal to the current flowing through the outer probes and the film.

Voltage sensing means 40 comprises a differential amplifier 58 and an ADC 60. The differential amplifier 58 in the preferred embodiment is an Analog Devices AD524 or equivalent amplifier. The differential amplifier 58 has two input leads which are coupled to the terminals I2 and I3, respectively, of the probe assembly connections 30. Terminals I2 and I3 are coupled to probes P2 and P3, respectively, of the probe assembly 22. Differential amplifier 58 senses the voltage V_{23} across terminals I2 and I3 and outputs a voltage adjusted according to the variable gain G_{23} of the differential amplifier 58. The gain G_{23} can be set to different levels by by the computer 44 by sending a control signal on control line 59 to set gain tabs on the differential amplifier 58. In the preferred embodiment, gain G_{23} can be set at 1, 10, 100, or 1000. The gain should be set to maximize the range of the ADC 60.

The output of the differential amplifier 48 is coupled to an ADC 60. Similar to the ADC 54 of the current sensing means 36, the ADC 60 has a resolution of twelve bits, so that a digital binary output from 0 to 4095 can be sent on a twelve bit bus 61 coupled to the output of the ADC 60. The bus 61 is coupled to an input port of the digital computer 44. The computer receives the data from the ADC over bus 61; the data is the digital signal B representing the voltage across probes P2 and P3 on the film surface 28.

Preferably DAC 46, amplifier 48, differential amplifiers 48 and 52, and ADC's 54 and 60 are provided on a plug-in board for computer 44. Alternatively, the DAC 46 and the ADC 60 are provided on a plug-in board for computer 44 and the amplifiers are externally provided near the probe assembly 22.

Figure 4 shows graphs of the voltage waveforms used in this preferred embodiment of the present invention. The graph 66 of V_O shows the time-variant sawtooth-shaped waveform generated by the voltage source 34 and varying from -5 volts to +5 volts. Each cycle of the sawtooth-shaped waveform comprises an upwardly-sloping ramp 67, a downwardly-sloping ramp 68, and another upwardly-sloping ramp 69. The sawtooth-shaped waveform has the advantage of being substantially continuous, thereby avoiding any sudden jumps in current that may

cause hysteresis effects in the measurements. The sawtooth-shaped waveform of V_O includes a number of voltage steps, each step corresponding to a number preferably between 0 and 4095 output by the computer 34. The sawtooth-shaped waveform is thus made up of 2048 steps in the upward-sloping ramp 67, 4096 steps in the downward-sloping ramp 68, and 2048 steps in the upwardly-sloping ramp 69. The graph 70 of V_{sense} and the graph 71 of V_{23} (i.e. the voltage across probes P2 and P3) show the same sawtooth-shaped voltage waveform shown in the V_O graph. This relationship shows that the current across the sense resistor and the voltage across the probes P2 and P3 vary substantially in phase with the source voltage, so that for each point in the V_O waveform, a corresponding V_{sense} and V_{23} can be measured.

Figure 5 is a flow diagram of a method 72 of measuring film thickness. The method begins at step 74, and, in a step 76, the probe assembly is engaged with a surface of the film which is to be measured for thickness. The film is made of a conductive material that allows a current to flow. The most typical application is the measurement of the thickness of metal films deposited on semiconductor wafers.

The probe assembly 22 is brought into contact with the surface 28 of the film so that all of the probes P1-4 are touching the surface. This can be done by moving either the probe assembly 22 or the substrate 29. The probes P1-4 are preferably spring-loaded so that they relieve pressure on the film surface when initially brought in contact with the surface, and so that they all make good contact with the film.

In a step 77, the measuring system is calibrated. The goal of the calibration is to adjust the measured voltages V_{sense} and V_{23} so that they are within the voltage range of the ADCs 54 and 60. The variable gains G_{14} and G_{23} of the differential amplifiers 52 and 58 are set by the computer 44 by control lines 53 and 59, respectively. To correctly set the gains, the computer outputs a voltage V_O, which is approximately 1 or 2 volts in the preferred embodiment, and receives an initial measurement from signals A and B from the four point probe assembly 22 so that the range of the measured voltages V_{sense} and V_{23} is known. The computer 44 then sets the gains G_{14} and G_{23} with the control lines 53 and 59 so that the output of the differential amplifiers 52 and 58 is in the range of the ADCs 54 and 60.

In a step 78, the process of measuring the sheet resistance of the surface of the film is described. A time-variant waveform V_O is sent by the voltage source 34 to the probe assembly 22 to create a current through the film. This current creates a voltage between the inner probes P2 and P3. The voltages V_{sense} and V_{23} are measured by

the differential amplifiers and a sheet resistance is calculated by a digital computer for the film. The process is described in detail subsequently.

In a step 80, a digital computer calculates the film thickness, which is calculated using the formula:

$$Thickness(cm) = \frac{\rho}{R_{sheet}}$$

where ρ, the resistivity of the film in ohm-cm, is a known value for the film material. R_{sheet} is the sheet resistance, which is the resistance value calculated in step 78 from the measured voltages V_{sense} and V_{23}. There are several methods to compute film thickness. The method in the preferred embodiment is to calculate a film thickness from the R_{sheet} value calculated in step 78 from a least squares line fit. Another method is to calculate a film thickness for each measured R_{sheet} value stored in step 78 and then average the film thicknesses. A third method is to calculate the film thickness from an average R_{sheet} value calculated in step 78. After the film thickness is calculated, the method is completed as indicated in step 82.

Figure 6 is a flow diagram of the method 86 of measuring sheet resistance of a film, shown in step 78 of Figure 5. The method starts with step 88 and, in step 90, counter variables j and R are initialized to zero. In a step 92, voltage V_O from the voltage source 34 is set to zero volts, which is equal to the number 2048 on a scale from 0 to 4095 in the preferred embodiment. Vo is compared to the maximum level V_{max} of V_O, which is the number 4095. If V_O is greater than or equal to V_{max}, then the upward ramp 67 of the sawtooth is complete, and the next step is step 100, described below. If V_O is less than V_{max}, then V_O is output on bus 47 by the voltage source 24 in a step 94. Index variable j is incremented in step 96, and input signals A and B are read in and stored as subscripted variables A(j) and B(j) in step 98. Signals A and B represent the voltages V_{sense} and V_{23}, respectively, read by the differential amplifiers 52 and 58. Once the values of signals A and B are stored in step 98, then V_O is incremented by the computer in step 92 and compared again to V_{max}. Until V_O reaches the maximum voltage, the computer increments V_O, outputs V_O, and stores the signals A and B measured at that V_O value. Once the voltage V_O is at the maximum level, the first ramp 67 of the sawtooth waveform is complete and step 100 is initiated.

Step 100 begins the downwardly-sloping ramp 68 of the sawtooth waveform as seen in Figure 4. V_O is set at the maximum voltage V_{max}, corresponding to the

number 4095 in the preferred embodiment. V_O is compared to zero; if it is less than or equal to zero, the ramping is complete, and the next step is 108 (described below). If V_O is greater than zero, then voltage source 24 outputs V_O on bus 47 in a step 102. Index variable j is incremented in step 104, and input signals A and B are read as subscripted variables A(j) and B(j) in step 106. Signals A and B represent the voltages V_{sense} and V_{23}, respectively, read by the differential amplifiers 52 and 58. The values of signals A and B are stored in step 106, and the value of V_O is decremented in step 100. The loop continues in the same manner so that V_O is outputted on bus 47 each time it is decremented and signals A and B are read and stored in the computer for each level of V_O. When V_O reaches -5 volts (the number 0), the downwardly-sloping ramp 68 is complete and step 108 is initiated.

Step 108 begins the final upwardly-sloping ramp 69 of the V_O waveform cycle as seen in Figure 4. V_O is set at the minimum voltage V_{min} corresponding to the number 0 in the preferred embodiment. V_O is compared to V_{mid} (equal to 2048); if it is greater than or equal to V_{mid}, the ramping is complete, and step 116 is initiated. If V_O is less than zero, then V_O is output and signals A and B are measured and stored by the computer in a similar fashion as described for steps 92-98 above. When V_O reaches 0 volts (the number 2048), the upwardly-sloping ramp is complete and step 116 is initiated.

The voltage source 34 can vary the voltage V_O very quickly, and thus many voltage measurements A and B are taken in a given time period. Since a voltage is being varied, no delay time for allowing a current level to stabilize in a current source is necessary.

Steps 116 and 118 are optional. In a step 116, variable R is incremented. R stores the count of cycles that the voltage V_O has cycled through. A cycle has occurred each time the voltage V_O is incremented through an upwardly-sloping ramp and decremented through a downwardly-sloping ramp. Each cycle preferably consists of 8192 levels of V_O, so that there are 8192 different sets of stored A and B data. Alternatively, every other level of Vo can be ignored so that 4096 sets of data are measured.

In a step 118, the variable R is compared to the REPEAT variable. The REPEAT variable contains the number of cycles that the user wishes the voltage V_O to cycle through. Thus, in the preferred embodiment, REPEAT multiplied by 8192 equals the total number of different measurements taken on the film surface. If R is less than REPEAT in step 118, another cycle of the V_O waveform is initiated at step

92. If R is greater than REPEAT, step 120 is initiated. In the preferred embodiment, one cycle of the voltage waveform is always used for any film, resulting in 8192 measurements (or 4096 if every other step in the waveform is ignored). In this case, REPEAT is always set to 1, and steps 116 and 118 are not required.

The value of the sheet resistance of the film R_{sheet} is calculated next using a least square line fit of the measurement voltage values stored in the previous steps. In step 120, a least square line fit is calculated from the data points of stored values A(j) and B(j) (see Figure 7). As explained above, there are up to 8192 data points stored in the preferred embodiment. The method for generating a least square line fit with existing data is well-known in the art. R_{sheet} is proportional to the slope m of the least square line. The equation describing the least square line is:

$$V_{23} = V_{23}^{0} + m V_{sense}$$

Ignoring V_{23}^{o}, which contains DC offsets of the entire electronic system, the slope m is equal to:

$$slope = m = \frac{V_{23}}{V_{sense}}$$

R_{sheet} is calculated from the known equation:

$$\begin{aligned} R_{sheet} &= 4.562\frac{V_{23}}{I_{sense}} = 4.562\frac{V_{23}}{V_{sense}} R_{sense} \\ &= 4.562\, m\, R_{sense} \end{aligned}$$

where I_{sense} is the current flowing through the film, R_{sense} is the known resistance of the sense resistor 50, and V_{sense} is the voltage across the sense resistor. V_{sense} and V_{23} are stored in the computer as values A(j) and B(j), respectively. R_{sheet} is calculated using the known formula 4.562(V/I) that assumes the four probes of the probe assembly 22 are spaced equally apart. In step 122, the computer multiplies the factor 4.562, the slope of the least square line, and the resistance of the sense resistor 50 to get R_{sheet} for the tested film. Once the R_{sheet} value is calculated, the process is complete, as indicated in step 124.

Other methods can be used to calculate a sheet resistance R_{sheet} from the measurement data, such as an averaging method. An R_{sheet} value can be calculated for each set of A and B data. All the R_{sheet} values can then be added together and

divided by the total number of measurements taken to get the average R_{sheet} value. The least square line fit method is used in the present embodiment, since it is insensitive to offsets in circuit components, as described in Figure 7.

Using the above-described process, more measurements can be taken in a given time period. With a greatly increased amount of measurements, the accuracy of the calculations for sheet resistance and film thickness are also greatly increased.

Figure 7 is a graph 126 showing the measurement points 128 of the voltages V_{23} and V_{sense} and the least squares line 130 calculated from the measurement points 128. The measurement points 128 are approximately linear, so that if a single measurement is much different from the other measurements, that measurement point 128 in graph 126 is spaced far from the least squares line 130 and is thus easy to single out.

As described above, R_{sheet} is proportional to the slope of the least square line 130, and the slope of the line 130 is calculated in order to determine the value of R_{sheet}. Since a slope is measured, undesired offsets in the voltage source 34 or other electronic components in the system do not affect the accuracy of the R_{sheet} measurement. Line 130 may cross the origin of the axes of graph 126, indicating no offset in the differential amplifiers, or the line may cross the axes at a different point as shown in Figure 7, indicating that an offset exists in the system. This offset, however, does not affect the accuracy of the resistance measurement.

In using a sawtooth-shaped waveform as the voltage source, the measurement points are taken when V_{23} and V_{sense} are either both negative or both positive, and the measurement points 128 appear in the first and third quadrants of the graph. This has the effect of reducing hysteresis effects, such as magnetic effects, that occur on the film surface when a current is induced in the film. Also, the sawtooth-shaped waveform is a substantially continuous waveform and thereby avoids any large jumps in voltage and current that could occur from discontinuities. Such discontinuities can cause hysteresis effects in the film. By taking measurements with a continuous sawtooth-shaped waveform in the first and third quadrants of the graph of Figure 7, one effectively degausses the measurement.

In Figure 8, a wafer handling apparatus 210 comprises a chuck assembly 212, a wafer pick 214, a probe assembly 22, a wafer cassette assembly 218, a computer 220, and test circuitry 222.

Chuck assembly 212 comprises a base platform 228, a testing chuck 230, and a drive assembly 232. Base platform 228 is preferably a table structure that supports testing chuck 230 and allows drive mechanism 232 to be located underneath the testing chuck. Testing chuck 230 is preferably a disc-shaped chuck that rotates around a central z-axis. Testing chuck 230 is also operative to move upwardly or downwardly along the z-axis perpendicular to the surface 234 of the testing chuck (the z-axis). In its fully lowered position, the testing chuck 230 rests in a circular groove 236 of base platform 228. A wafer 238 rests on the surface 234 of testing chuck 230 and can engage probe assembly 22 when testing chuck 230 is raised adequately and probe assembly 22 is positioned over the testing chuck 230. Other workpieces besides wafers can also be placed on chuck 230 and tested.

Testing chuck 230 includes a slot 237 extending radially from the center of testing chuck 230 to an edge of the chuck. The slot is about one-fourth an inch deep and $1\frac{1}{4}$ inches wide. Testing chuck 230 also includes concentric vacuum grooves (not shown) which are operative to hold wafer 238 to the surface of the testing chuck when coupled to a vacuum pump. Such vacuum chucks are well-known in the art.

Drive assembly 232 is operative to rotate testing chuck 230 and to move testing chuck 230 up and down the z-axis. The drive assembly comprises a pulley 240, a first motor 242, and a second motor 244. Pulley 240 is connected to testing chuck 230 by a shaft 246 that extends through the base platform 228 through suitable bearings (not shown). Pulley 240 is connected to motor 242 by a drive belt 248. Motor 242 rotates pulley 240 and thereby rotates shaft 246 and testing chuck 230. Motor 242 is connected to a support 250 of motor 244. One end of support 250 is provided with a threaded nut 254 which engages a lead screw 252 coupled to a shaft of motor 244. Threaded nut 254 can be an anti-backlash nut or a ball screw nut. The support 250 is connected to the main shaft 246 by bearing 256. The far end of support 250 is secured to the motor 242 by a secure connection, such as a welding connection, and to guide shaft 251. The motor 244 is positioned on a fixed surface 253 that supports base platform 228. When the shaft of motor 244 rotates, the support 250 moves along the z-axis and carries the shaft 246, pulley 240, motor 242, and testing chuck 230 along the z-axis. The bearing 256 of support 250 allows the shaft 246 to rotate freely while still being securely held by the support 250.

Motors 242 and 244 are preferably stepper motors controlled by computer 220 through main bus 257. The computer can rotate the stepper motors in either direction

with precise steps, allowing the testing chuck to rotate and move in the z-axis in small, precisely-defined increments.

Alternatively, the testing chuck 230 can be moved parallel to the x-axis 259 in addition to being rotated. This movement can be implemented by positioning parallel tracks on the sides of the base platform 228 and moving the chuck assembly 212 along the tracks using wheels or gears. The movement can be driven by a stepper motor similar to motors 242 and 244. In such an embodiment, the wafer 238 can be completely tested using a stationary probe assembly 22 and moving only the testing chuck 230.

Wafer pick 214 includes a pick shuttle 260 and a wand 262. Pick shuttle 260 is coupled to a lead screw 264 supported by a base support 266. The central axis of lead screw 264 is positioned horizontally parallel to x-axis 259. In the preferred embodiment, the pick shuttle 260 includes a threaded nut 268 that engages lead screw 264. The screw 264 helps hold the wafer pick 214 and is also operative to move the wafer pick in a direction parallel to the x-axis 259.

The other end of pick shuttle 260 is connected to wand 262. Wand 262 extends towards the wafer cassette assembly 218 (detailed below) about six inches and is parallel to x-axis 259. Wand 262 is aligned with slot 237 in testing chuck 230 so that wand 262 can fit within slot 237. Wand 262 includes apertures 270 that are coupled to a vacuum pump to securely hold a wafer or similar workpiece to the wand by atmospheric pressure. Vacuum wands are well-known to those skilled in the art.

Motor 272 is coupled to lead screw 264 and is operative to rotate the lead screw 264. When lead screw 264 is rotated, wafer pick 214 moves along the x-axis along the length of the shaft. Motor 272 is preferably a stepper motor and is precisely controlled by computer 220 to position wafer pick 214.

Other mechanisms can be used to move the wafer pick parallel to the x-axis. For example, the pick shuttle 260 can be driven along a rod by motor gears. Or, the shuttle can be driven by a hydraulic or pulley system. Any mechanism that provides precise movement and control will function for pick shuttle movement.

Probe assembly 22 preferably comprises probe arm 274 and test head 276, which can. On one end, probe arm 274 is preferably connected to a lead screw 277 supported by base support 266. Probe arm 274 includes a threaded nut 279 that

engages screw 277, permitting probe arm 274 movement parallel to the x-axis along the length of the screw 277.

On its other end, probe arm 274 is connected to test head 276. The test head preferably includes probes 278 which are designed to take test measurements on the wafer surface. In the preferred embodiment, probe assembly 22 includes a four-point probe apparatus, including the housing 26 and test probes P1, P2, P3, and P4 (see Figure 2), for measuring the thickness of thin films that is described with reference to Figures 2-7.

Probe arm 274 is operative to position the test head 276 over variable locations on the wafer 238. The probe arm 274 moves parallel to the x-axis along lead screw 277 by the use of motor 280. Motor 280 rotates lead screw 277, which moves probe arm 274 along the lead screw 277. Motor 280 is preferably a stepper motor controlled by computer 220.

In other embodiments, different mechanisms can be used to move the probe assembly along the x-axis. These mechanisms include similar mechanisms as those discussed above for the pick shuttle 260.

In still other embodiments, the probe arm can be set up to move in both the x-axis and y-axis directions. In such an embodiment, lead screw 277 is able to move in the y-axis direction by the use of tracks or guides positioned on both sides of the shaft 276. The probe arm moves in the x-direction along the shaft, and moves in the y-direction as the shaft moves along the y-axis. In such an embodiment, the rotation of testing chuck 230 is not required to test the entire surface of the wafer and may be eliminated (see Figure 12).

Wafer cassette assembly 218 includes a cassette 282 and a drive assembly 284. Cassette 282 is preferably an industry standard tray designed to hold a number of wafers 285. The cassette 282 is positioned on one side of the chuck assembly 212 with its opening facing the testing chuck 230 and the wand 262. The bottom wafer 285 in the cassette 282 is positioned at a height slightly above the height of wand 262 of wafer pick 214 so that the wand can move beneath the bottom wafer. Once the wand is beneath the wafer, the cassette 282 is lowered so that the wafer is situated on the wand 262. The pick 214 is then moved back towards the chuck 230.

Drive assembly 284 includes a brace 286, a lead screw 288, and a motor 290. The brace 286 is attached to the back of cassette 282. The brace can also include a

platform which supports the cassette 282. Brace 286 includes a threaded nut 292 engaged with lead screw 288. Screw 288 is rotated by motor 290. Motor 290 is positioned on a stable surface 253 below the cassette 282. As screw 288 rotates, brace 286 moves upwardly and downwardly parallel to the z-axis along part of the length of the shaft, and carries cassette 282. Motor 290 is preferably a stepper motor and is computer-controlled. Cassette 282 can be positioned to align a particular wafer in the cassette 282 with the wand 262 of wafer pick 214. When a wafer is tested and replaced in the cassette, the cassette is moved to align the next wafer to be tested with the wand 262. In this way, all the wafers in the cassette 282 can be tested.

Cassette 282 can be removed from brace 286 when all the wafers in the cassette have been tested. A similar cassette can then be connected to the brace 286 to allow new wafers to be tested. Alternately, the same cassette can be removed from brace 286, unloaded and loaded with new wafers, and reconnected to brace 286.

Computer 220 preferably comprises a microprocessor-controlled digital computation apparatus that is coupled to the wafer handling apparatus by a bus 257. The computer 220 can control the stepper motors 242, 244, 272, 280 and 290 of the apparatus to accomplish the wafer handling and testing process.

Test circuitry 222 comprises circuitry operative to control the test head 276 of the probe assembly 22. Test circuitry 222 is coupled to the test head 276 by a bus 292.

Figures 9a-9d illustrate several top plan views of the apparatus 210. Figure 9a shows an initial state of the wafer handling apparatus 210 where the probe assembly 22 and wafer pick 214 are at a starting position. The process is initiated when the probe assembly 22 and the wafer pick 214 are both moved towards the wafer cassette assembly 218 as indicated by the arrows M1 and M2, respectively.

Figure 9b shows the wafer loading position of the probe assembly 22 and wafer pick 214. Probe assembly 22 is positioned close to cassette assembly 218 so that wand 262 of wafer pick 214 can extend into the cassette assembly. The wand 262 is positioned beneath wafer 238 in cassette 282, and the vacuum pump coupled to the wand 262 is activated, securing wafer 238 to the wand 262. The cassette assembly 218 may be slightly lowered. The wafer pick 214 then is moved back towards the testing chuck 230 as indicated by arrow M3.

Figure 9c illustrates the placement of the wafer 238 on the testing chuck 230. Wafer pick 214 is positioned so that the wafer 238 is centered over the testing chuck 230. Testing chuck 230 is elevated so that the wand 262 fits into slot 237 and the surface of testing chuck 230 engages the bottom surface of the wafer 238, lifting the wafer off of the wand 262. The vacuum pump connected to wand 262 is deactivated, and the vacuum pump connected to chuck 230 is activated.

Figure 9d shows the testing positions of the probe assembly 22 and wafer pick 214. Wafer pick 214 retracts from testing chuck 230 and probe assembly 22 is positioned over the wafer 238 as illustrated by arrows M4 and M5, respectively. Preferably, the center and flat of the wafer are found using a commercially available flat and center finder. Once probe assembly 22 is positioned in the desired testing position, testing chuck 230 elevates a small distance to engage the surface of the wafer 238 with the probes of the test head. The measurements are taken, and the testing chuck moves down to disengage the wafer with the test head. If more test points on the wafer are to be tested, the chuck 230 is rotated and/or the probe assembly 22 is translated and the next test point is tested (see Figure 12). If the measuring process is over, the wafer pick puts the wafer back into the cassette assembly 218 using the reverse of the procedure described above. The process is repeated for the next wafer positioned above the last wafer tested in the cassette, until all the wafers have been tested.

Figure 10 is a side elevational view of the wafer handling apparatus 210. The various motions of the chuck assembly 212, wafer pick 214, probe assembly 22, and wafer cassette assembly 218 are shown with arrows. The position of the drive assembly 232 relative to the testing chuck 230 is also shown. In the present embodiment, the probe arm and pick shuttle are at the same level on the z-axis and thus cannot move past one another.

The test head 276 of probe assembly 22 is positioned higher than the wand 262 of wafer pick 214. This positioning allows the wafer 238 to be lifted from the wand 262 and still have enough space to engage the test probes 278 of the test head.

A total of five motions are shown in Figure 10. The probe assembly 22 has movement parallel to the x-axis , the wafer pick 214 has movement parallel to the x-axis , the testing chuck 230 has movement parallel to the z-axis and rotational movement around the z-axis, and the wafer cassette 282 has movement parallel to the z-axis .

Figure 11 is a flow diagram 294 of the wafer handling process. The process begins at a step 296 and, in a step 298, the cassette 282 holding wafers 285 is positioned parallel to the z-axis so that a wafer that has not been tested is positioned at about the same level as wand 262 of wafer pick 214. In step 300, probe assembly 22 and wafer pick 214 are moved to the cassette so that the wand 262 is positioned under the wafer to be tested.

In step 301, the wafer 238 is secured to the wand 262 by activating the vacuum pump coupled to apertures 270. The wafer is removed from the cassette in step 302 and the wafer pick 214 is positioned over the testing chuck 230. Testing chuck 230 elevates to lift the wafer off the wand 262 and holds the wafer to the testing chuck using vacuum slots.

In step 304, the wafer pick 214 deactivates the vacuum suction through holes 270 and withdraws in the direction opposite to the wafer cassette 282. In step 306, the wafer 238 is tested. The testing process is described in detail with reference to Figure 10. Once the testing is complete, the wafer pick 214 and probe assembly 22 are moved in step 308 to replace the tested wafer back into the cassette 282. This is done in the reverse process as described above: the chuck 30 elevates, the wand 262 moves under wafer 238 through slot 237, and the chuck lowers and leaves the wafer on the wand. The probe assembly and wafer pick are then moved to the cassette assembly 218 to replace the wafer back to its slot in the cassette 282.

In step 310, the wafer pick 214 and probe assembly 22 are moved away from the cassette assembly 218 to their resting positions. Next, in step 312, the computer checks if any more wafers in the cassette need to be tested. This can be checked in a variety of ways. The operator can input to the computer the number of wafers in the cassette before the testing process begins. The computer stores the number in a variable and decrements the number every time a wafer is completely tested. When the number reaches zero, there are no more wafers in the cassette to be tested.

Alternately, a sensing apparatus can be used on the wafer cassette assembly. The sensing apparatus can be a photodetector or similar device that senses if a wafer occupies a slot in the cassette. If no wafer occupies the slot, the cassette is moved to the next slot position. The process continues until all the slots in the cassette have been sensed.

Once all of the wafers are tested, the process is complete as indicated in step 314. The wafer cassette 282 can be removed and another placed on the apparatus to begin another cycle of wafer testing.

Figure 12 is a flow diagram 318 showing the process of testing a wafer. The wafer 238 has been placed on the chuck and the wafer pick 214 has retracted. The process starts in a step 320 and, in a step 321, a wafer flat, notch, or index mark is oriented and the wafer center is found. Flat-orientation can be accomplished by rotating the wafer by rotating the chuck 230 so that the wafer edge passes through a emitter/photodetector and blocks a detector from detecting an emitted beam. As the flat rotates through the beam, the beam is detected and the flat position is known and can be oriented in a certain direction. The center of the wafer is typically found by determining the coordinates of the perimeter of the wafer. Once the coordinates of the wafer center are determined, the computer 220 can compensate for any off-centeredness of the wafer or the chuck. Preferably, the wafer is either a larger diameter than the chuck 230, or a transparent chuck can be used so that the photodetector can detect the wafer edge through the chuck. Suitable wafer flat orienters and center finders are made by Brooks Automation of Santa Clara, California, and Genmark Automation of Sunnyvale, California.

Once the wafer center is located, step 322 is initiated. The probe assembly 22 is positioned over the wafer 218. The initial position of the probe assembly is preferably near the center of the wafer that was found in step 321.

In step 324, the status of the test is examined by the computer. The positioning of the probe assembly 22 indicates when the entire wafer has been tested. In the preferred embodiment, the probe assembly starts testing at the center of the wafer and incrementally moves parallel to the x-axis towards the outer edge of the wafer after the chuck incrementally rotates through 360 degrees (see below). In the preferred embodiment, the test head 276 is positioned at 25 to 1000 test points from the center to the edge of the wafer for a eight-inch wafer. When the probe assembly is positioned past the final testing position on the edge, the test is complete as indicated in step 326. In the preferred embodiment, the computer senses when the probes 278 of a four-point probe are no longer touching the wafer, since no current flows between the outer probes through the wafer.

If the probe assembly is not positioned at its final testing position as indicated in step 324, then, in a step 328, testing chuck 230 is rotated by f degrees. The angle f that the chuck rotates is determined by the desired distance between test points on the

wafer surface. If the operator wishes to test many points, the chuck rotates a small amount, e.g. 10°. The angle can also be variable, so that less points can be tested close to the center of the wafer where there is less circumference using a larger angle of rotation, and more points can be tested close to the edge of the wafer using a smaller angle of rotation. In the preferred embodiment, the chuck incrementally rotates by about 0.04 degrees.

In alternate embodiments, the chuck need not be rotated to test all the points on a wafer surface. The probe arm 274 can be set up to move along the x-axis and the y-axis and thus test all of the points on the wafer surface in a grid pattern. In such an embodiment, the probes 278 of the test head 276 can test points along x-axis rows and y-axis rows as detailed below with reference to Figure 13.

In another embodiment, the probe assembly can be stationary, while the chuck can elevate, rotate, and move along the x-axis or the y-axis. This latter embodiment tests the wafer in the same test point pattern as the preferred embodiment, with the main difference being that the chuck is the only moving part.

In step 330, the computer checks if a full rotation (i.e. 360°) of the chuck has been completed. If a full rotation has been completed, the probe assembly 22 is positioned to the next testing position parallel to the x-axis as indicated in step 322. If a full rotation has not been completed, the test point is tested as indicated in steps 332 through 336.

In step 332, the testing chuck 230 raises to engage the wafer surface with the probe assembly at the current test point. This is accomplished as described with reference to Figure 9. In step 334, the testing is completed. The tests can include resistivity measurements of the wafer, sheet resistance measurements of the film on the wafer surface, or any other kind of test performed on a wafer. Test circuitry 222 is used to perform the tests.

In step 336, testing chuck 230 is lowered to disengage the wafer surface from the test head. The process then starts again at step 328, where the chuck is rotated to the next test point and the computer checks if a full rotation has been completed. In this way, substantially the entire surface of the wafer is tested in consecutive concentric rings going out from the center to the edge of the wafer 218.

Figures 13a, 13b and 13c show patterns of testing points on a wafer surface. Figure 13a shows a top plan view of a pattern of testing a wafer as described in Figure

12. Wafer 238 is tested by probe assembly 22 at several test points 338. The test head 276 starts testing the wafer at a test point near the center 340 of the wafer surface, such as test point 341. A circle 342 of test points is tested by incrementally rotating the chuck to each test point on the circle. When circle 342 has been tested, the probe assembly moves parallel to the x-axis to circle 344, where testing continues. Circles of test points are tested in this manner until the probe assembly reaches the outer edge 346 of the wafer.

Alternatively, the test points can be tested in a pattern as shown in Figure 13b. In this pattern, the probe assembly 22 starts testing at a point at the edge 346 of the wafer 238, such as at test point 348. After a point is tested, the probe assembly moves parallel to the x-axis and tests another point. Test points are tested in this linear manner along line 349 until the probe reaches the opposite edge 350 of the wafer. The wafer is then incrementally rotated, and the probe assembly starts testing another line of test points 352. Several diameters or chords across the wafer surface are thus tested using this pattern, and substantially the entire wafer surface is tested.

Figure 13c shows an alternative testing pattern that can be used with the present invention. The probe assembly 22 or the testing chuck 230 moves parallel to the x-axis and the y-axis so that a grid of test points 354 is tested. The probes 278 of the test head 276 can test each test point along an x-axis row 356, then move slightly along the y-axis and test each point along the next x-axis row, and so on. The grid pattern can also be accomplished by moving the probe assembly along the x-axis and rotating the chuck simulataneously to test the desired pattern of points.

While this invention has been described in terms of several preferred embodiments, it is contemplated that alterations, modifications and permutations thereof will become apparent to those skilled in the art upon a reading of the specification and study of the drawings. It is intended that the claims include all such alterations, modifications and permutations as fall within the spirit and scope of the present invention.

What is claimed is:

CLAIMS

1. An apparatus for measuring film thickness comprising:

a probe assembly including four probes;

means for engaging said probe assembly with a surface of a film;

current sensing means;

voltage source means coupled to said probe assembly by said current sensing means to create a current in said film when said probe assembly is engaged with said surface of said film by said means for engaging;

voltage sensing means coupled to said probe assembly to sense a voltage between two probes of said probe assembly; and

means for determining film thickness from said measured current and said measured voltage.

2. An apparatus for measuring film thickness as recited in claim 1, wherein said means for engaging includes a chuck means for supporting a wafer to be tested in an x-y plane, said chuck means being positioned below said probe assembly.

3. An apparatus for measuring film thickness as recited in claim 2, wherein said means for engaging includes means for selectively moving said chuck means along a z-axis substantially perpendicular to said x-y plane to cause an upper surface of said wafer to engage and disengage said probes of said probe assembly.

4. An apparatus for measuring film thickness as recited in claim 3, wherein said means for engaging includes means for moving at least one of said probe assembly and said chuck means in a plane substantially parallel to said x-y plane.

5. An apparatus for measuring film thickness as recited in claim 1 wherein said current sensing means includes a sense resistor between said voltage source means and one of said probes.

6. An apparatus for measuring film thickness as recited in claim 5 wherein said current sensing means includes voltage sensing means for sensing a voltage across said sense resistor.

7. An apparatus for measuring film thickness as recited in claim 1 wherein said voltage source means provides at least two different voltage levels at two different points in time, and wherein said current in said film and said voltage between two probes are sensed at both of said two points in time.

8. An apparatus for measuring film thickness as recited in claim 1 wherein said voltage source provides a substantially sawtooth-shaped waveform.

9. An apparatus for measuring film thickness as recited in claim 1 wherein said voltage source includes a digital processing apparatus.

10. An apparatus for measuring film thickness as recited in claim 9 wherein said voltage source includes a digital to analog (D/A) converter coupled to an output of said digital processing apparatus. and an amplifier coupled to an output of said D/A converter.

11. An apparatus for measuring film thickness as recited in claim 1 wherein said current sensing means includes a sense resistor, differential amplifier means having its inputs coupled across said sense resistor, analog to digital (A/D) converter coupled to an output of said differential amplifier, and digital processing means having an input coupled to an output of said A/D converter.

12. An apparatus for measuring film thickness as recited in claim 1 wherein said voltage sensing means includes differential amplifier means having its inputs coupled to said two probes of said probe assembly, analog to digital (A/D) converter coupled to an output of said differential amplifier, and digital processing means having an input coupled to an output of said A/D converter.

13. A method as recited in claim 1 wherein said means for engaging said probe assembly with a surface of a film is operative to engage said probe assembly with a plurality of locations on the film surface.

14. An apparatus for measuring film thickness as recited in claim 13 further comprising:

means for calculating a sheet resistance for each location thus engaged using said sensed current and said sensed voltage; and

means for calculating said film thickness from said plurality of measured sheet resistances.

15. A wafer testing apparatus comprising:

a tester means;

chuck means for supporting a wafer to be tested in an x-y plane, said chuck means being positioned below said tester means;

means for selectively moving said chuck means along a z-axis substantially perpendicular to said x-y plane to cause an upper surface of said wafer to engage and disengage said tester means; and

means for moving at least one of said tester means and said chuck means in a plane substantially parallel to said x-y plane.

16. A wafer testing apparatus as recited in claim 15 further comprising handling means operative to position said wafer on said chuck means.

17. A wafer testing apparatus as recited in claim 16 wherein said handling means includes vacuum pick means.

18. A wafer testing apparatus as recited in claim 16 wherein said handling means includes means for moving said handling means in a plane parallel to a plane of said tester means.

19. A wafer testing apparatus as recited in claim 15 wherein said tester means includes a four-point probe assembly.

20. A wafer testing apparatus as recited in claim 19 wherein said tester means includes current sensing means and voltage source means coupled to said probe assembly by said current sensing means to create a current in said film when said four-point probe assembly is engaged with said surface of said film by said means for selectively moving.

21. A wafer testing apparatus as recited in claim 20 wherein said tester means includes voltage sensing means coupled to said probe assembly to sense a voltage between two probes of said probe assembly.

22. A wafer testing apparatus as recited in claim 21 wherein said tester means includes means for determining film thickness from said sensed current and said sensed voltage.

23. A wafer testing apparatus as recited in claim 15 wherein said means for moving at least one of said tester means and said chuck means in a plane substantially parallel to said x-y plane includes chuck rotating means.

24. A wafer testing apparatus as recited in claim 15 wherein said means for moving at least one of said detector means and said chuck means in a plane substantially parallel to said x-y plane includes means for moving said tester means in an x-direction.

25. A wafer testing apparatus as recited in claim 24 wherein said means for moving at least one of said detector means and said chuck means includes a carriage moved along a screw rotated by a stepper motor.

26. A wafer testing apparatus as recited in claim 15 further comprising control means operative to coordinate said means for selectively moving and said means for moving.

27. A wafer testing apparatus as recited in claim 26 further comprising means for finding the center of said surface of said wafer coupled to said control means.

28. A wafer testing apparatus as recited in claim 26 further comprising means for finding an index mark of said wafer coupled to said control means.

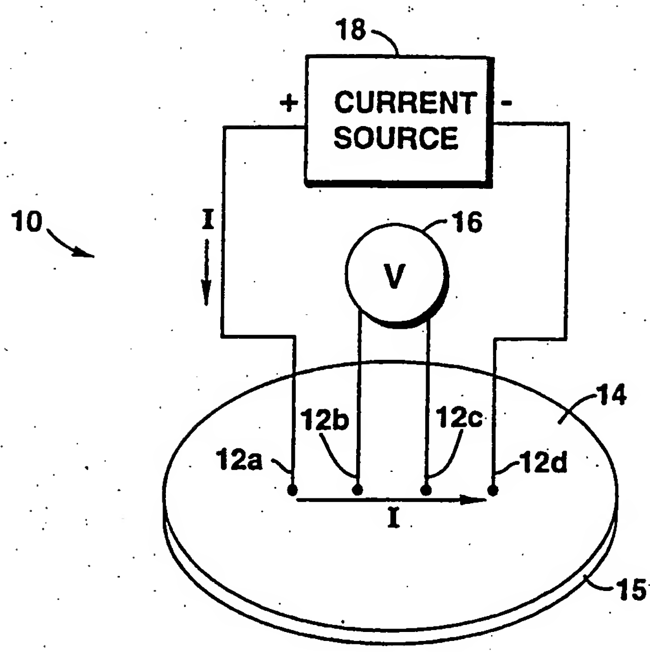

Figure 1
(Prior Art)

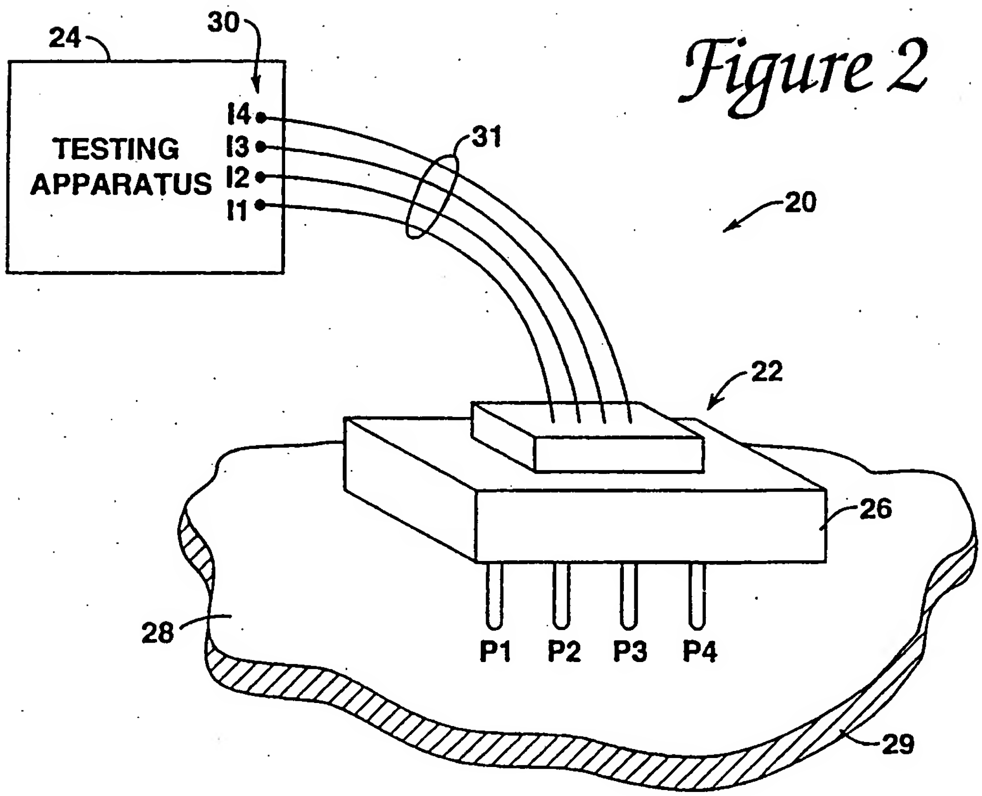

Figure 2

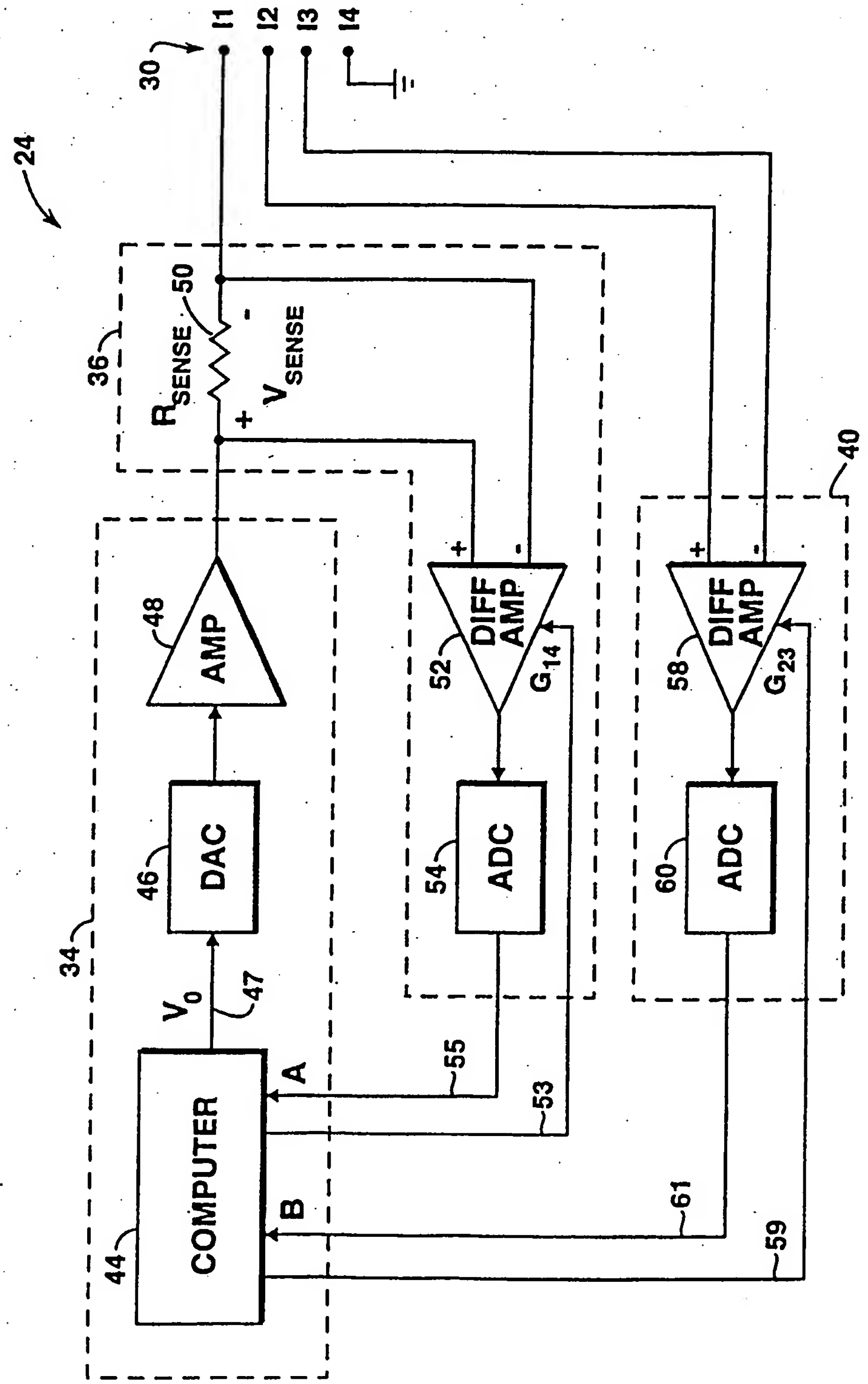
24
30
I1
I2
I3
I4
36
R_{SENSE}
50
V_{SENSE}
+
-
34
AMP
48
DAC
46
V_0
47
COMPUTER
44
A
B
55
53
61
59
52
DIFF AMP
G_{14}
ADC
54
40
58
DIFF AMP
G_{23}
ADC
60

Figure 3

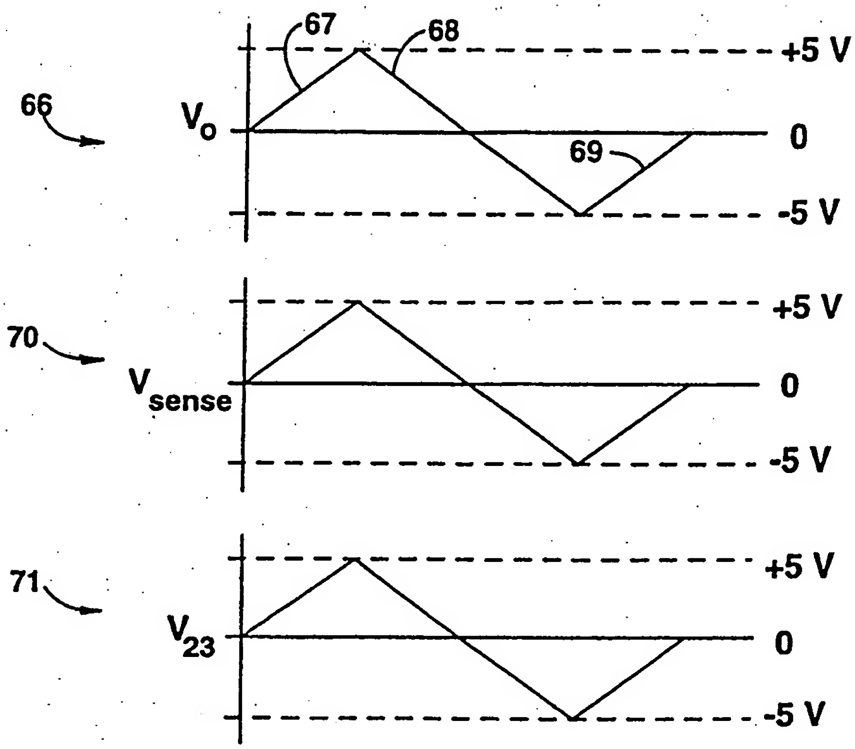

Figure 4

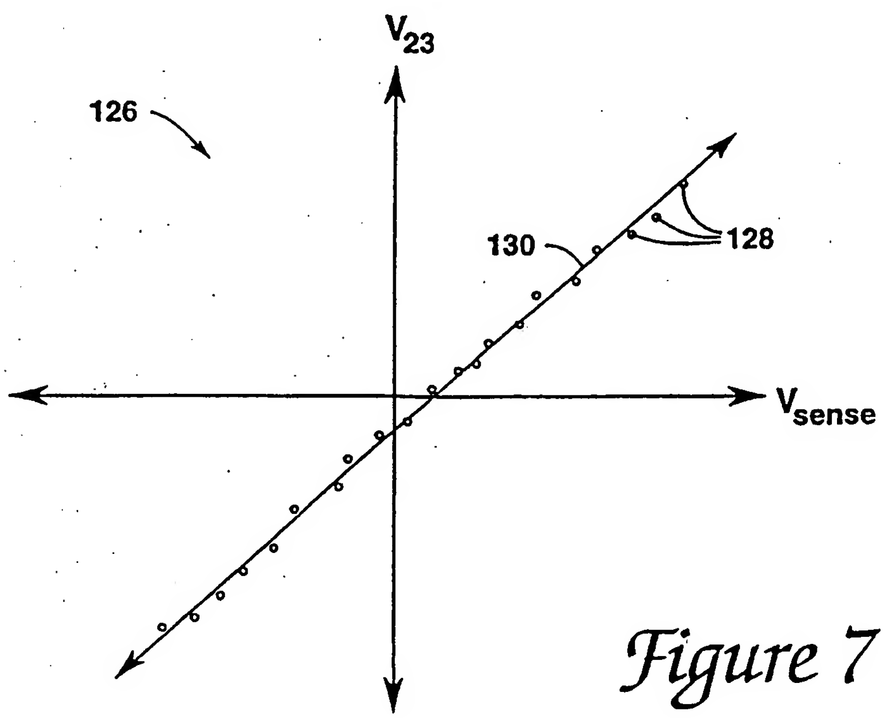

Figure 7

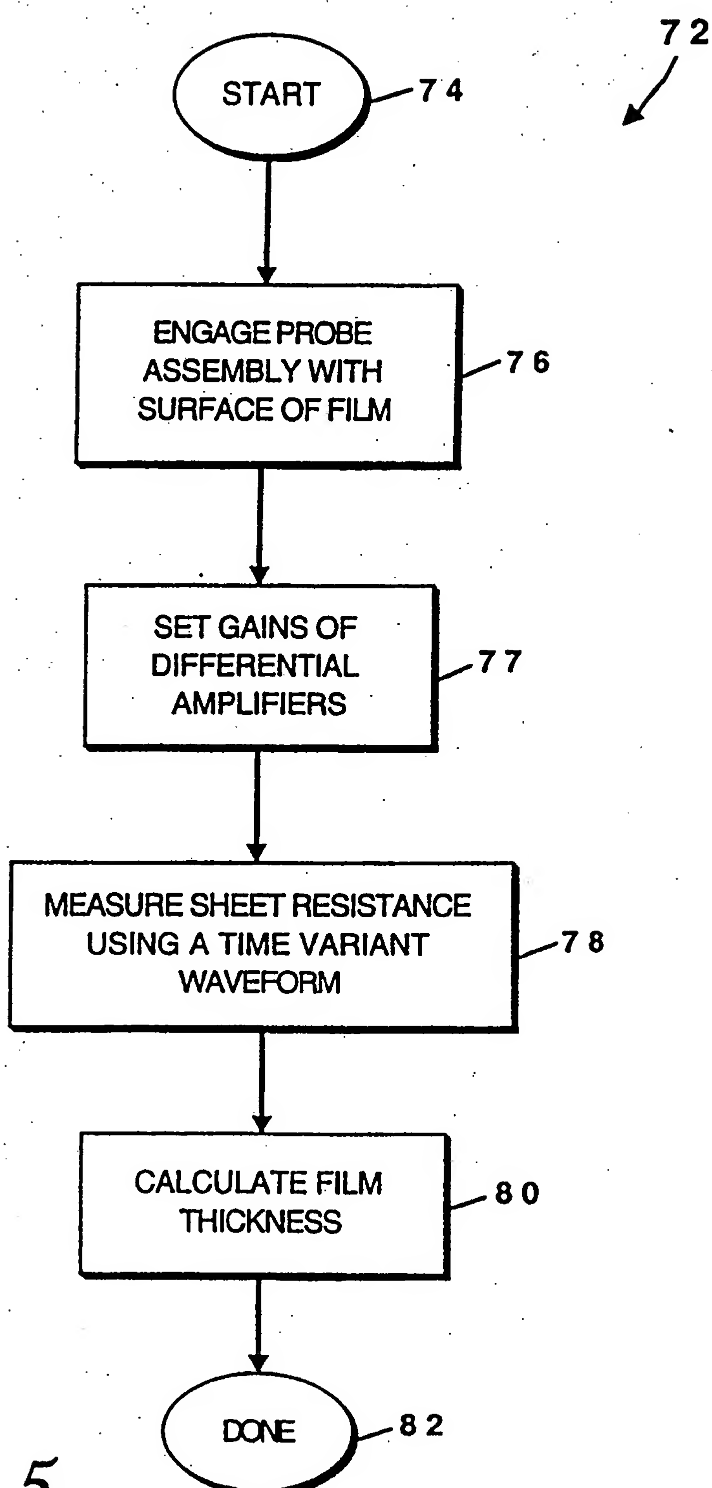
72
START
74
ENGAGE PROBE ASSEMBLY WITH SURFACE OF FILM
76
SET GAINS OF DIFFERENTIAL AMPLIFIERS
77
MEASURE SHEET RESISTANCE USING A TIME VARIANT WAVEFORM
78
CALCULATE FILM THICKNESS
80
DONE
82

Figure 5

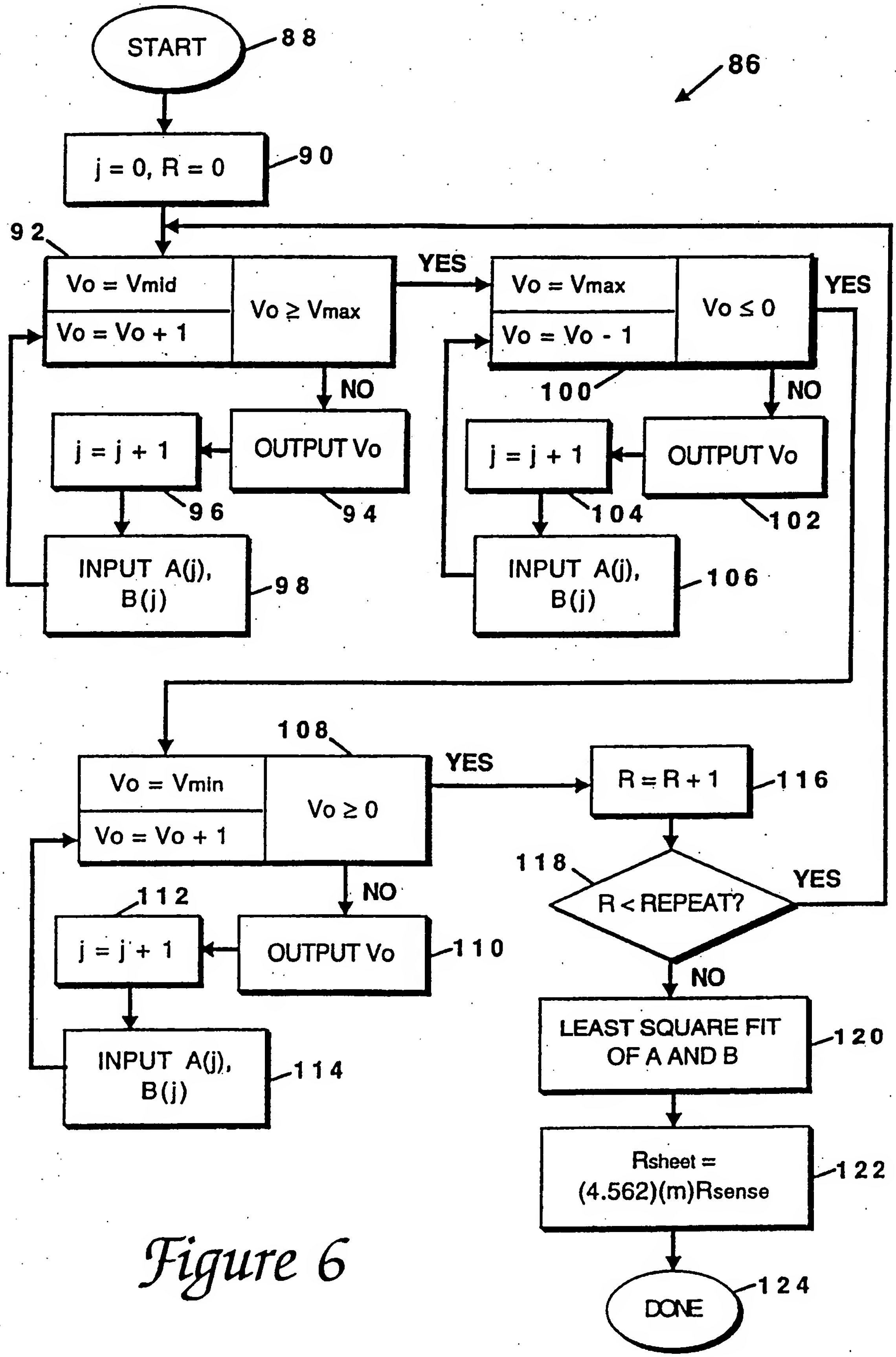
START
88
86
j = 0, R = 0
90
92
Vo = Vmid
Vo = Vo + 1
Vo ≥ Vmax
YES
Vo = Vmax
Vo = Vo - 1
Vo ≤ 0
YES
NO
100
NO
j = j + 1
OUTPUT Vo
96
94
j = j + 1
OUTPUT Vo
104
102
INPUT A(j), B(j)
98
INPUT A(j), B(j)
106
108
Vo = Vmin
Vo = Vo + 1
Vo ≥ 0
YES
R = R + 1
116
118
R < REPEAT?
YES
NO
112
j = j + 1
OUTPUT Vo
110
NO
INPUT A(j), B(j)
114
LEAST SQUARE FIT OF A AND B
120
Rsheet = (4.562)(m)Rsense
122
DONE
124

Figure 6

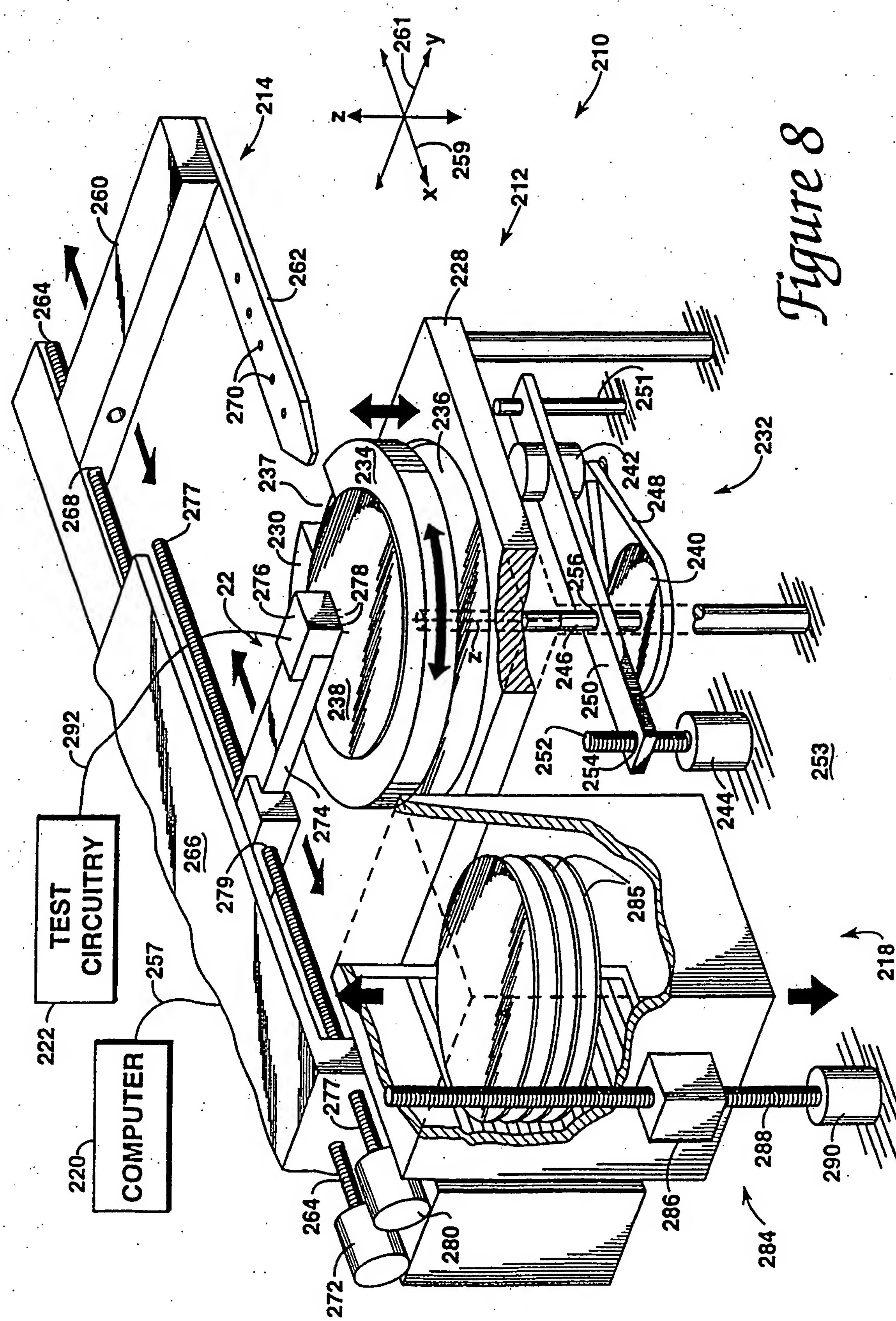

Figure 8

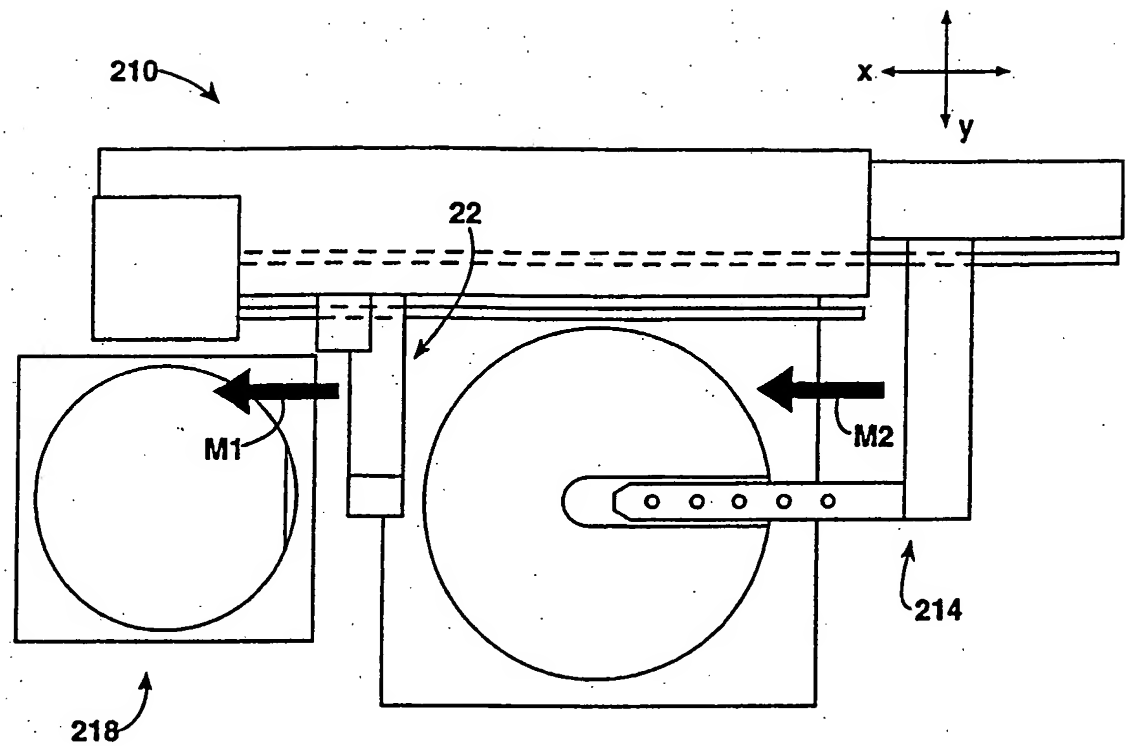

Figure 9a

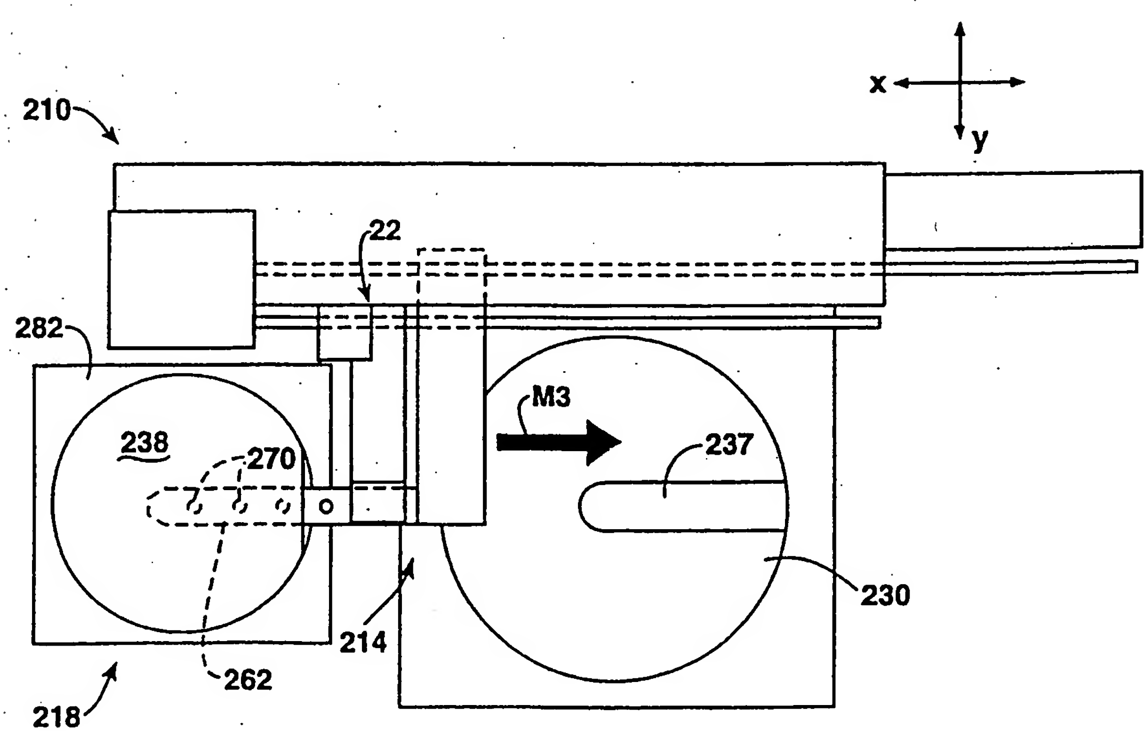

Figure 9b

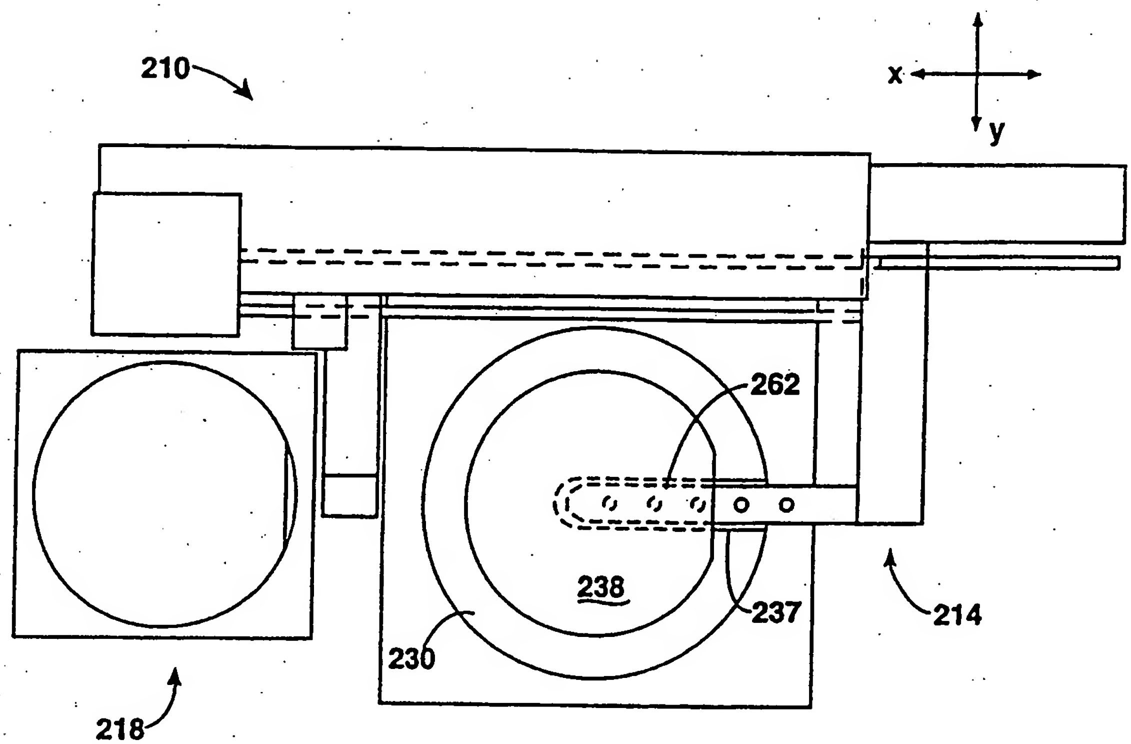

Figure 9c

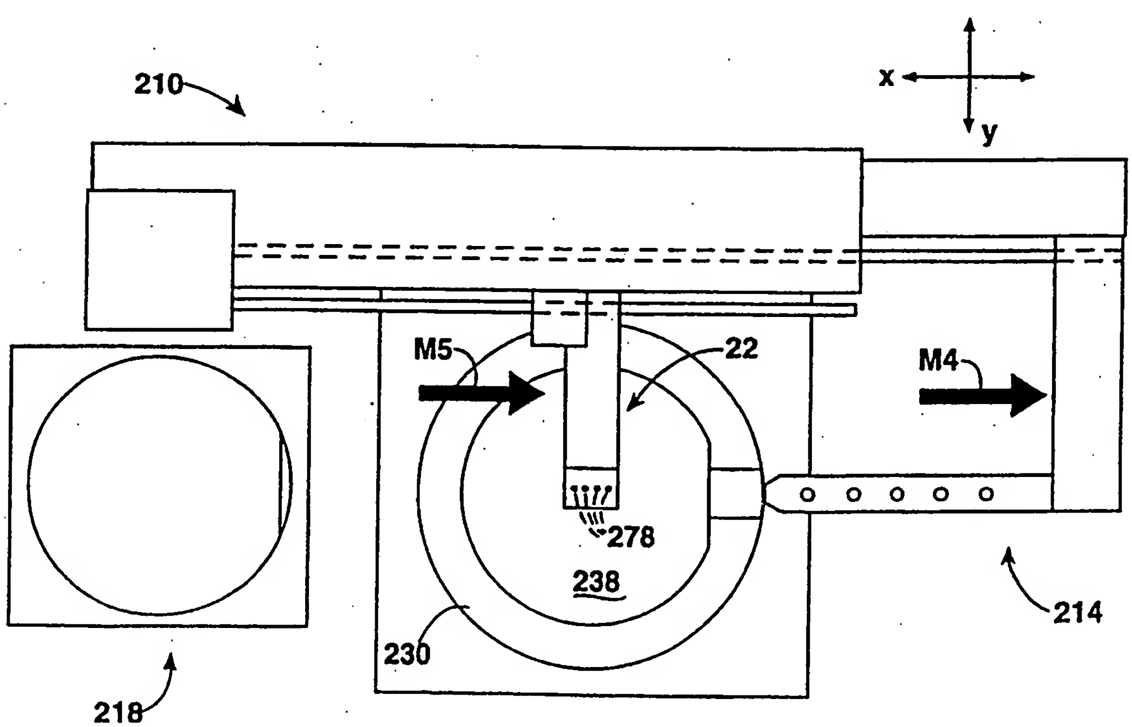

Figure 9d

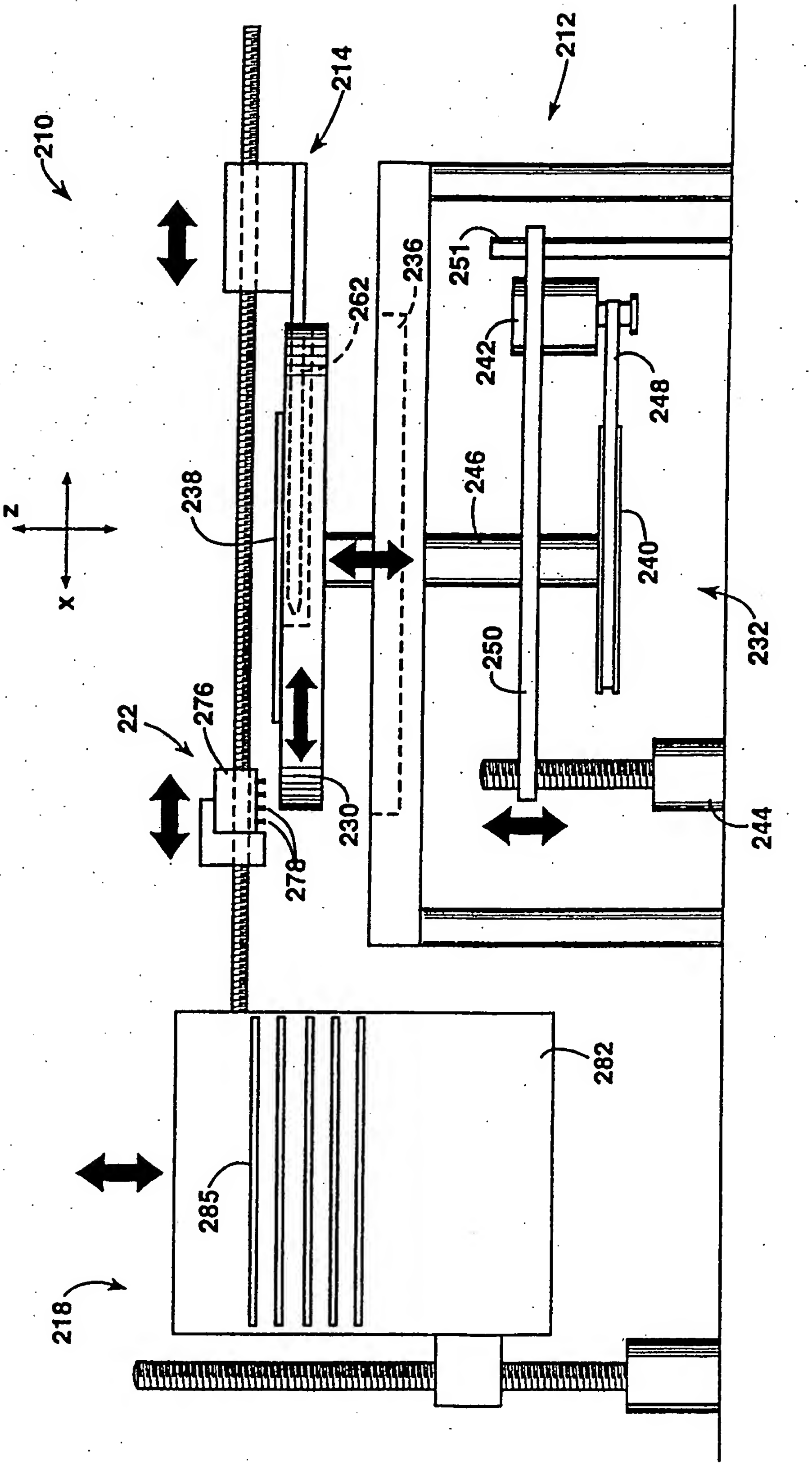
210
214
212
262
236
251
242
248
238
246
240
232
250
z
x
22
276
230
244
278
282
285
218

Figure 10

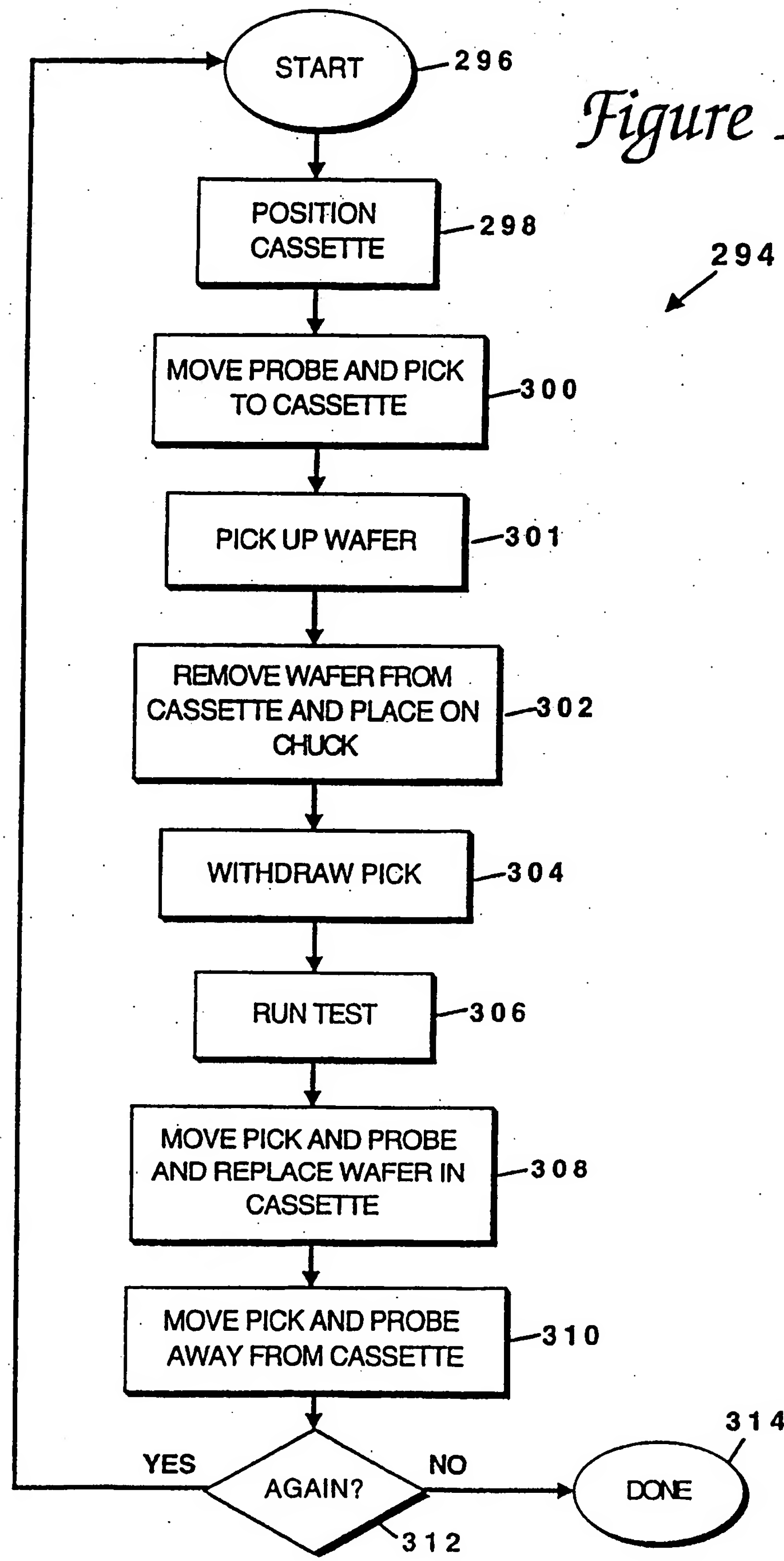
START
296
POSITION CASSETTE
298
MOVE PROBE AND PICK TO CASSETTE
300
PICK UP WAFER
301
REMOVE WAFER FROM CASSETTE AND PLACE ON CHUCK
302
WITHDRAW PICK
304
RUN TEST
306
MOVE PICK AND PROBE AND REPLACE WAFER IN CASSETTE
308
MOVE PICK AND PROBE AWAY FROM CASSETTE
310
YES
AGAIN?
NO
312
DONE
314
294

Figure 11

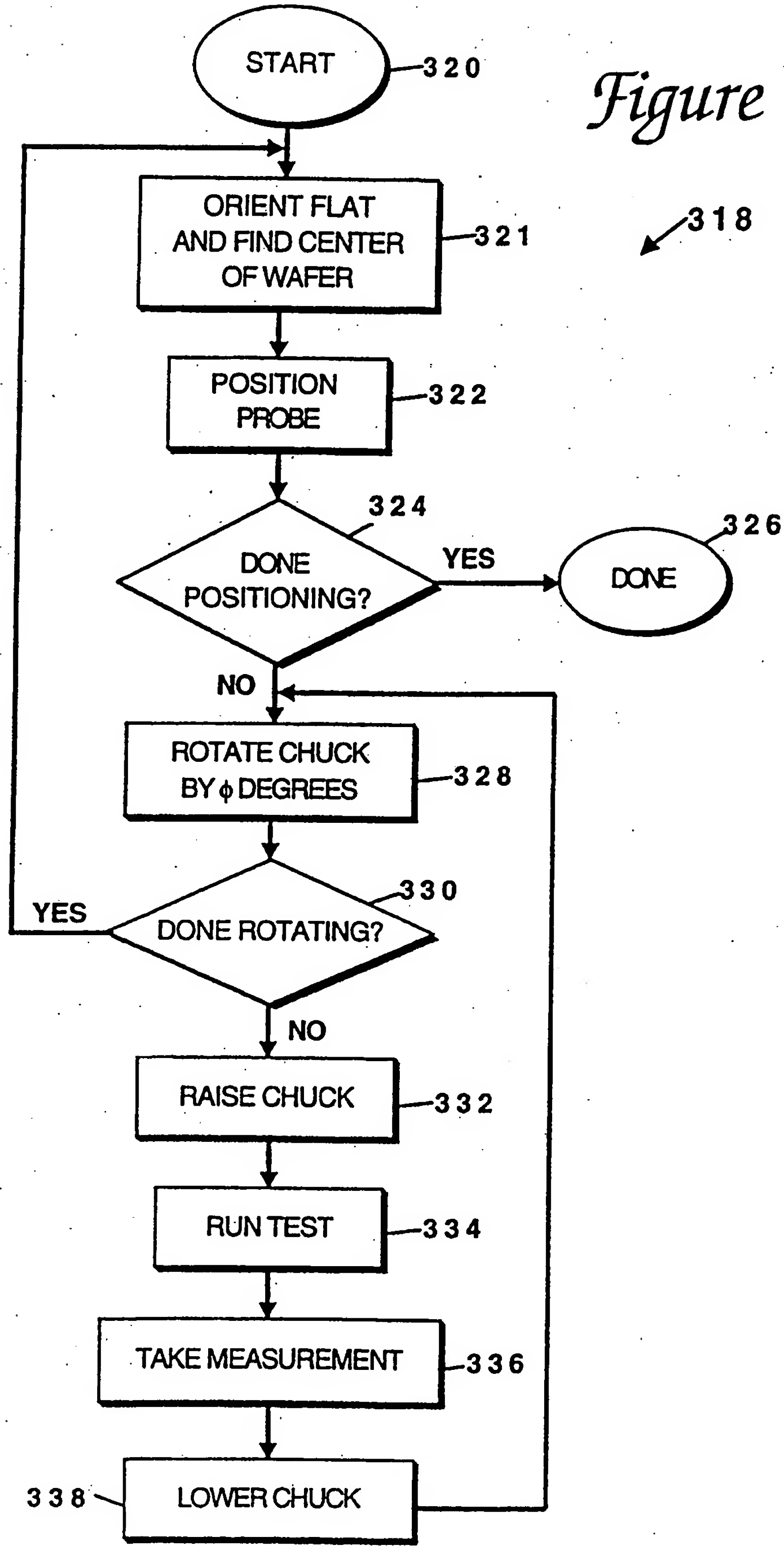
START
320
ORIENT FLAT AND FIND CENTER OF WAFER
321
POSITION PROBE
322
324
DONE POSITIONING?
YES
DONE
326
NO
ROTATE CHUCK BY ϕ DEGREES
328
330
YES
DONE ROTATING?
NO
RAISE CHUCK
332
RUN TEST
334
TAKE MEASUREMENT
336
338
LOWER CHUCK
318

Figure 12

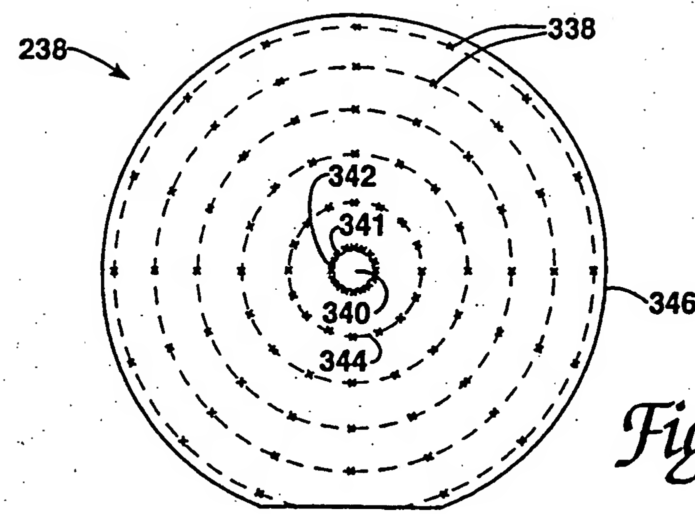

Figure 13a

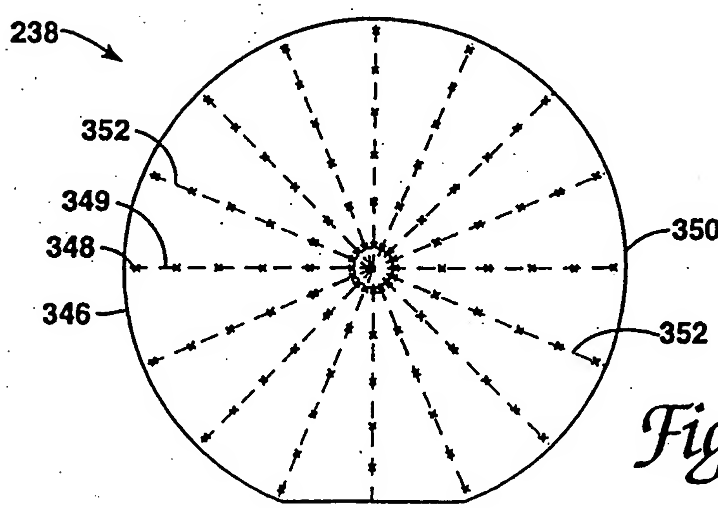

Figure 13b

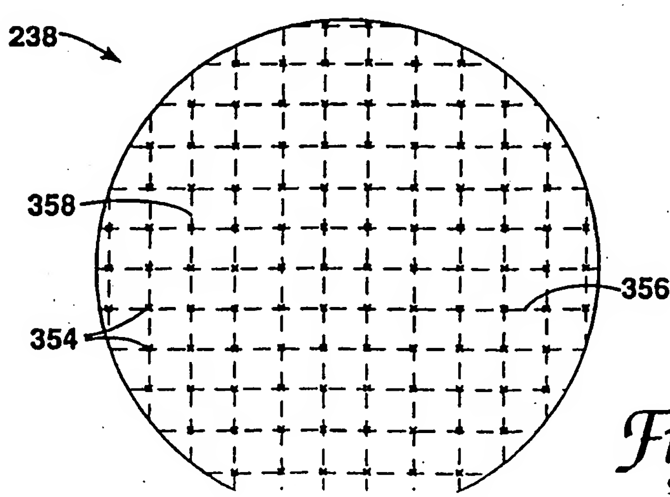

Figure 13c

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US93/11076

A. CLASSIFICATION OF SUBJECT MATTER

IPC(5) :G01R 27/02; B65G 1/00
US CL :324/716,158F; 414/416
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 324/713, 715, 716,158F,158R,158D; 414/416,331

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US, A, 4,989,154 (YAMASHITA ET AL.) 29 JANUARY 1991. SEE FIGURE 12 AND COLUMNS 18-19.	1,7, 9-12, 14
Y	US, A, 4,546,318 (BOWDEN) 08 OCTOBER 1985. SEE FIGURE 1 AND THE ABSTRACT	5-6,8
A	US, A, 2,659,861 (BRANSON) 17 NOVEMBER 1953. SEE FIGURE 1	1
A	US, A, 3,735,254 (SEVERIN) 22 MAY 1973. SEE FIGURE 5.	13
X	US, A, 3,676,775 (DUPNOCK) 11 JULY 1972. SEE FIGURE 1 AND COLUMN 2.	1
X	US, A, 4,929,893 (SATO ET AL.)29 MAY 1990. SEE FIGURE 1 AND COLUMN 2, LINES 14-19.	2-4, 15, 19, 23, 26

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be part of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search 01 MARCH 1994	Date of mailing of the international search report APR 05 1994
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. NOT APPLICABLE	Authorized officer MAURA REGAN Telephone No. (703) 305-4917

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US, A, 4,775,281, (PRENTAKIS) 04 OCTOBER 1988. SEE COLUMN 1, LINES 50-58.	16, 17, 18, 20-22, 24, 25, 27-28.